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Search for the optimal window-to-wall ratio in office buildings in different European climates and the implications on total energy saving potential

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Abstract

This paper deals with the search for the optimal window-to-wall ratio (WWR) in different European climates in relation to an office building characterized by best-available technologies for building envelope components and installations. The optimal WWR value is the one that minimizes, on an annual basis, the sum of the energy use for heating, cooling and lighting.

By means of integrated thermal and lighting simulations, the optimal WWR for each of the main orientations was found in four different locations, covering the mid-latitude region (35° to 60° N), from temperate to continental climates. Moreover, the robustness of the results was also tested by means of sensitivity analyses against the efficiency of the building equipment, the efficacy of the artificial lighting and the compactness of the building.

The results indicate that although there is an optimal WWR in each climate and orientation, most of the ideal values can be found in a relatively narrow range (0.30 < WWR < 0.45). Only south-oriented façades in very cold or very warm climates require WWR values outside this range. The total energy use may increase in the range of 5–25% when the worst WWR configuration is adopted, compared to when the optimal WWR is used.

Keywords: Window-to-wall ratio (WWR); Passive solar architecture; Low-energy office buildings; Energy conservation; Integrated thermal-lighting simulations

1. Introduction

1.1. Background

The façade – and in general the entire building envelope – can be considered the main system for solar energy conversion at the building scale. Even without considering the possibility of incorporating active systems, such as building integrated photovoltaics (BIPV) (Jelle et al., 2012) or an integrated solar thermal panel (Matuska and Sourek, 2006), the configuration of the façade itself plays a role in the way solar energy is exploited within the building. First of all, the balance between glazing and opaque areas alone has an impact on many aspects of the energy balance, influencing solar gain (and thus energy use for heating and cooling) and heat loss (mainly affecting energy use for heating), but also daylight availability (with implications on

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Nomenclature

ACH	Air Change per Hour (h^{-1})
DA	Daylight Autonomy (%)
E	(specific) energy (kW h m^{-2})
HVAC	Heating, Ventilation and Air Conditioning
SA:V	Surface Area over Volume ratio (m^{-1})
SCOP	Seasonal Coefficient of Performance (–)
SHGC	Solar Heat Gain Coefficient (–)
UDI	Useful Daylight Illuminance (%)
WWR	window-to-wall ratio (–)

Subscript

C	cooling
EE	electrical energy
H	heating
L	(artificial) lighting
NC	night cooling (free cooling)
PE	primary energy
TOT	total

energy use for artificial light). Second, the use of solar shading systems increases the capability of the façade to dynamically control solar gain and daylighting in order to improve further the building's energy performance and passive solar energy exploitation. Finally, the selection of materials and components with appropriate thermal and optical properties greatly influences all aspects of the total energy balance when the building envelope is used as the control volume on the indoor environment, i.e. the space to be conditioned and kept within a certain comfortable range.

The influence of the façade configuration in preserving a comfortable indoor environment was previously related to the energy for space heating alone, while implications on cooling and artificial light energy use have only become the subject of dedicated research activities in the last few decades. However, in the present-day R&D panorama, aimed at reaching the nearly Zero Energy Buildings (nZEB) target (Marszal et al., 2011), the influence of the building envelope needs to be fully evaluated from a total energy approach, i.e. considering heating, cooling and artificial light use together.[1]

From this perspective, the optimization of the façade configuration is not a straightforward problem: measures to minimize one aspect (e.g. the energy use for heating) often have a negative impact on the others (e.g. on the energy use for cooling and artificial lighting). The optimal solution is thus the best compromise of different possibilities and needs to be found by means of an integrated (thermal and lighting) approach.

Among all the aspects involved in the design of a façade system, the window-to-wall ratio (WWR) – i.e. the ratio between the transparent area and the opaque surface[2] – is a parameter that has a deep impact on both the energy balance (Lee et al., 2013; Shen and Tzempelikos, 2013) and architectural appearance of the construction. The "transparency" of a building is often set more by looking at the architectural and aesthetic implications rather than at the energy performance. Moreover, this choice is often made in the very first stage of the design process and will not be subject to later changes, while many other aspects (such as materials, equipment and operations) can be more easily decided and modified at a later stage. The selection of an appropriate WWR value for a façade should thus be carried out at the very beginning using an energy-wise approach, and it is therefore important that this selection is made carefully.

1.2. Window-to-wall ratio and climate: a short overview

The first records (Arumi, 1977; Johnson et al., 1985, 1984) concerning dedicated investigations into the impact of the WWR on the energy balance of a building showed that selecting an optimal WWR value would have halved the energy use. In general, the early research showed that for each climate and orientation it was possible to find an optimum WWR that minimized the annual energy use. It is important to highlight that potential for energy saving was quite significant and that these analyses did not include the use of solar shading systems. A short overview of the development of the research activities about the impact of the WWR can be found in Goia et al. (2013).

It is worth noting that some of the articles available (e.g. Johnson et al., 1985, 1984) tackled the impact of the transparent percentage of the façade from the perspective of the climate.

[1] As defined in the European Standard EN 15603 ("EN 15603:2008 – Energy performance of buildings – Overall energy use and definition of energy ratings," 2008), the annual energy use of a building is given by the sum of the annual energy use for heating, cooling, lighting, ventilation and humidification, hot water and other services. The first three elements are those directly affected by the façade configuration while the others can be considered independent from it.

[2] In this paper the term WWR identify the ration between the net transparent area and the total opaque area and not the ratio between the window surface (including the frame) and the total façade area (i.e. the area of the frame of the window is included in the total opaque area; this means, for example, that in a façade with an area of 10 m^2 and a WWR of 0.20, the area of the glazed unit is 0.20 m^2).

For example, the impact of the WWR for south- and north-facing façades in five Turkish locations, characterized by different climates (Csa, Dsa and Dfb, according to Peel et al. (2007)) but within a limited latitude range, was investigated by Inanici and Demirbilek (2000). The case study was a mid-size residential building and only thermal simulations were carried out. The results showed that different climates required different window sizes, ranging from very high values of WWR (up to 0.90 in Dsa and Dfa climates) down to low values (0.25 in the Csa climate). The role of some other variables was investigated in this paper too, including the insulation level of the opaque walls.

The mutual influence between insulation and the WWR was also analyzed in a more recent article, still in Turkish climates, by Özkan and Onan (2011). Through an investigation that covered energy savings over a lifetime of 10 years, and payback periods, the research showed that a low WWR and highly insulated walls should always be preferred, regardless of the climate. However, this research, as with Inanici and Demirbilek (2000), only focused on heating energy use.

Integrated thermal and daylighting simulations to determine the ideal window area were carried out for two climates (Leeds, UK, Cfb; Florianapólis, Cfa) by Ghisi and Tinker (2005). Unfortunately, the saving potential for different window areas was only calculated for artificial lighting energy, without evaluating the impact from a total energy perspective. Therefore, just considering the artificial lighting energy use, the energy savings that could be achieved by an optimal window area were assessed to be in the range of 10–44% and 20–86% for Leeds and Florianapólis, respectively.

More recently, Kheiri (2013) studied the relationship between window area and climates using four locations around the world: Miami, USA – Am; Las Vegas, USA – Bwh; Sheffield, UK – Cfb; St Petersburg, Russia – Dfb. Simulations took into account energy for heating and cooling, but no shading systems were adopted. It is worth mentioning that the adopted façade technologies (glazing and opaque surface) were characterized by standard solutions not suitable for low or very low-energy buildings (i.e. *U-values* for windows, walls and other opaque surfaces were in the range of 2.4–2.9 $\mathrm{W\,m^{-2}\,K^{-1}}$); results were therefore deeply affected by these boundary conditions. The outcome of this investigation showed that the WWR had an optimum value in the range of 0.20–0.32, while a higher WWR caused a nonlinear increase in thermal energy loads and a lowering of lighting loads – the former being much more relevant than the latter. Furthermore, the glare discomfort risk increased when a large transparent area was adopted. North- and west-facing façades in colder climates and a west-facing façade in warmer and drier climates were the most sensitive ones, with a significant increase in energy use when a non-optimal WWR was chosen.

A similar research activity is presented in the article written by Lee et al. (2013) which focused on the Asian region. In the paper, the annual heating, cooling and lighting energy use was optimized by changing different types of window systems and their properties, among which the WWR played a very relevant role. Five typical Asian climates were investigated: Manila, Philippines – Af; Taipei, Taiwan – Cfa; Shanghai, China – Cfa; Seoul, South Korea – Dfa; and Sapporo, Japan – Dfa. Through a regression analysis, the relationship between window properties and total energy performance was derived and an optimized window system for each climate determined. As far as the WWR is concerned, the main recommendation was to minimize the transparent percentage (suggested optimal WWR of 0.25), with exceptions for the north-facing façade in the warmest locations.

Once more, it is important to highlight that glazing systems were not equipped with devices for solar shading. Relatively low values of WWR are thus influenced to a great extent by this feature. Moreover, while highly insulated glazing systems were included in the simulations (with *U-values* as low as 0.8 $\mathrm{W\,m^{-2}\,K^{-1}}$), *U-values* for opaque walls (in the range of 2.05–3.17 $\mathrm{W\,m^{-2}\,K^{-1}}$) were not the best achievable with present-day technology.

The effect of geometry factors, including WWR, on fenestration energy performance in office buildings was investigated by Susorova et al. (2013). Six different locations in the USA were considered, including Cfa, Csb, Dfa and Dfb climates. The study showed that energy use can be affected by the WWR in hot climates and cold climates, but only marginally in temperate climates. However, energy savings from optimal configurations were somehow limited (on average 3% and 6%, reaching a maximum of 10% and 14%) in hot climates, and almost negligible (on average 1%) in temperate and cold climates. In warm climates, the main energy use reductions arose with a WWR of 0.50–0.80, while lower WWR values (0.20–0.60) were suggested for Dfa climates; in very cold locations, the best energy performance was achieved with small windows for the north-facing façade and with a WWR in the range of 0.50–0.80 for the south-facing façade.

These results are probably due to a series of boundary conditions: the fact that no shading systems were simulated (which introduce higher savings potential); in addition to energy use for heating, cooling and lighting being considered in the total energy balance, other entries that are not related to the façade – such as energy use for domestic hot water or ventilation fans – were included; energy saving potential was calculated with a WWR of 0.40, which is an average situation; and only office cell rooms were simulated, imposing five adiabatic surfaces and only one surface (the façade) with heat transfer.

It is also worth noting that opaque and transparent technologies employed in these simulations were in line with the minimum requirements for energy performance set by the ASHRAE Standard 90.1. However, the thermal resistance of glazing systems especially was quite low and not in line with best practice for very low-energy buildings in the climates investigated in the article (Cfa, Csb, Dfa and Dfb).

Méndez Echenagucia et al. (2015) presented an integrative approach for the early stages of building design to obtain detailed information on energy efficient envelope configurations. A multi-objective research was performed and the energy need for heating, cooling and lighting of a case study minimized by means of genetic algorithms. The investigation was carried out for an open space office building by varying number, position, shape and type of windows, as well as the thickness of the masonry walls. Analyses were conducted both in absence and in presence of an urban context, in four different climates (Csa, Cfa, Cfb and Dfb). The results of the simulations of the case studies revealed, in general, the optimal solution to be a small window-to-wall ratio (WWR) value, regardless of the location. However, it is important to highlight that the simulated case studies did not include any solar shading system.

In conclusion, even though several research activities have been carried out, and some of them in very recent years, there is a lack of analyses that include solar shading devices (a more and more common provision and a "must" in high-performance buildings) and best-available technologies for building envelope components and installations suitable for very low-energy buildings. In particular, the impact of intelligent glazed façades is very relevant, and may allow substantial energy savings to be achieved – e.g. a study on the potentials of dynamic façades in a Cfb climate (Liu et al., 2015) revealed that a glazed system with dynamic properties, among which shading systems, may reduce the energy use for operation by 60%; the same study also showed that the optimal WWR for an intelligent glazed façade in a Cfb climate is found around the value WWR = 0.40, in line with the findings in Goia et al. (2013).

1.3. Aim of the activity and research questions

The main scope of the research activity presented in this paper is to determine adequate WWR value ranges, close enough to the optimal WWR value, for low-energy office buildings equipped with high-performance systems and shading devices in different climates, orientations and, to a certain extent, for different configurations. In this context, the term "optimal WWR" means that value(s) that minimizes, on an annual basis, the sum of the energy use for heating, cooling and lighting, while the other aspects of the total energy use defined in EN 15603 ("EN 15603:2008 – Energy performance of buildings – Overall energy use and definition of energy ratings," 2008) are not considered since they are not directly affected by the WWR configuration. Other aspects that might be relevant for the façade configuration in a global optimization procedure (e.g. costs, environmental impact) are not taken into account in this research.

It is important to stress that the focus in this research is placed on "value ranges" rather than on a single value. This approach is chosen because of the following aspects: the intrinsic limitations of the adopted methodologies (numerical simulations have uncertainties as much as experimental data); the use of a case study; the sensitivity analyses; and the usefulness of the generated knowledge. In fact, it would probably be of little interest to identify the exact optimal value for each simulation, since it is not likely to be widely used in practice and would be limited to the configuration of the selected case study. On the contrary, it seems more significant to provide a range of good-enough values to enable researchers and practitioners to choose a WWR knowing that they are sufficiently close to the optimal solution. With this in mind, the aim is thus to provide a sort of "rule-of-thumb" rather than exact numbers to be used in the early stage of the design process, or to limit the field of investigation in other research activities related to the optimal performance of building and building envelope configuration. This approach can also be found in other publications (e.g. Bastien and Athienitis, 2015; Ma et al., 2015) where the focus is placed on developing simple tools that are useful at an early design stage in order to compare different design options.

In general, the optimal WWR value depends on the exact set of a very large number of variables that are set during the design process. In order to assess the reliability of the found solutions and to determine the WWR value ranges that are sufficiently robust to the changes (within certain limits) of some design parameters, a sensitivity analysis has also been carried out. Robustness of the optimal WWR values has been tested against different building compactness values (evaluated by means of the Surface-Area over Volume ratio, SA:V), different efficiencies of the HVAC system (evaluated by means of the Seasonal Coefficient of Performance, SCOP), and different efficiencies of the artificial lighting (evaluated by means of the luminous efficacy, η_L).

The research questions that drove this investigation were:

Q.1. If one exists, what is the optimal WWR value(s) that minimizes the sum of the energy use for heating, cooling and lighting (for each orientation, in a certain climate/location)?

Q.2. To what extent is the optimal WWR value sensitive to a change in (some) design parameters (such as compactness, HVAC efficiency, efficacy of artificial lighting)?

Q.3. What is the potential energy use reduction when the optimal WWR value is adopted compared to the worst WWR configuration (given a certain orientation and climate/location)?

Q.4. If one exists, what is the range of values close enough to the optimal WWR value and robust enough to some changes in some variables (sensitivity analysis) which can be used during the early stage of the design phase?

2. Research methodology

The method used to determine the optimal WWR value is derived from previous work presented in Goia et al. (2013), which was developed to assist the design of an advanced, multifunctional façade module (Favoino et al., 2016, 2014), prototyped and tested in a Cfa climate. In that paper (Goia et al., 2013), integrated thermal-lighting simulations, coupled with suitable data post-processing, were used to find the optimal configuration (optimal WWR value) for a low-energy office building in Frankfurt. In the following Sections 2.1–2.4, the main aspects of that methodology are briefly discussed for the sake of completeness. More detailed information is omitted in the text for the sake of brevity, but precise references to the mentioned article are made throughout the text where relevant.

2.1. Case study features and numerical simulation tool

2.1.1. Office building geometry and equipment

The simulated office building (base case, with SA:V of 0.25 m^{-1}) presents a “typical” plan with a central corridor and office cells on both sides of the corridor. Services, staircases and lifts are placed at the two ends of the corridor. On each side of the corridor, there are 12 office cells, with the following indoor dimensions: 3.6 m (w), 5.4 m (l), 2.7 m (h). The office building has seven floors with offices above the entrance floor. The external dimensions of the building are: 45.9 m (w), 14.4 m (l), 28.9 m (h). A schematic diagram of the office plan layout can be found in Goia et al. (2013) (Fig. 2).

Contrary to other similar research activities (e.g. Nielsen et al., 2011; Ochoa et al., 2012; Shen and Tzempelikos, 2012; Tzempelikos and Athienitis, 2007), where only the office cell is simulated, in the present work, the entire office building was simulated (a strategy that is also used in some other research, such as Ghisi and Tinker (2005), Pino et al. (2012) and Susorova et al. (2013)). After each simulation was carried out, the building was virtually divided, along the corridor axis, in two volumes (half of the total volume each). The performance of each half volume was then associated to one orientation only, considering that the building is considerably bigger in length than in width and it thus presents two main façades (e.g. the south- and north-facing façades, if the building corridor is aligned along the east–west axis) and two considerably smaller façades (e.g. east and west, in the above-mentioned example).

This procedure implies that each orientation also accounts for an energy use that is somehow associated to two other orientations. However, such a strategy allows a better evaluation of the actual energy use for each orientation to be calculated than the simulation of an office cell alone; this is because an office building not only includes office rooms but also other spaces.

Specifications of the building services settings and internal loads are given in Table 1, based on specifications suggested in “EN 15251:2008 – Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics” (2008) and Owen (2013).

The office building is equipped with an air-to-water heat pump system delivering energy for both space heating and cooling purposes. Regardless of the location of the office building (see Section 3), the characteristics of the heat pump are kept constant, while the resulting SCOP, $SCOP_H$ (heating) and $SCOP_C$ (cooling) depends on the climate. Specifications about $SCOP_H$ and $SCOP_C$ are given in Section 2.3.2.

2.1.2. Façade materials and geometry

Each office cell is equipped with a façade (exterior dimensions: 3.7 m (w), 3.2 m (h)) with high-performance (but market-available) materials and systems. Five different WWR values are used in this research (0.20; 0.35; 0.50; 0.65; 0.80), meaning that the transparent area ranges from 20% to 80% of the façade area. Further information on the dimensions and position of the window can be found in Goia et al. (2013), Fig. 1.

The glazing is a triple glass pane unit with low-e coatings and argon in the cavities ($U\text{-}value = 0.7\ \mathrm{W\,m^{-2}\,K^{-1}}$; $SHGC = 0.46$; $\tau_v = 0.53$) and an integrated external venetian blind system (angle continuously adjusted to block direct solar radiation). Different activation flux for displacement of venetian blinds are tested (solar irradiance on the vertical plane from 100 to 400 W m^{-2}) and the procedure for the selection of the optimal activation flux (see Section 2.2.2) is connected with the procedure for the determination of the optimal WWR. In fact, the optimal

Table 1
Settings for HVAC, internal loads, and lighting for the cell office rooms.

	Temperature set-point (heating/cooling)		HVAC		Internal loads		Lighting	
	Summer (°C)	Winter (°C)	Mechanical ventilation ($\mathrm{l\,s^{-1}\,m^{-2}}$)	Heat recovery efficiency (–)	Equipment ($\mathrm{W\,m^{-2}}$)	People ($\mathrm{W\,m^{-2}}$)	Installed power ($\mathrm{W\,m^{-2}}$)	Illuminance set-point (lx)
Occupancy Mon–Fri 8 am–5 pm	20/24	23/26	1.42	0.80	10.0	11.5	7.5	500
Non occupancy	17/27	20/29	0.70	0.80	1.0	0.0	7.5	0

activation flux is related to the transparent percentage of the façade.

The opaque surface of the façade is made with a sandwich panel characterized by a *U-value* of 0.15 $\mathrm{W\,m^{-2}\,K^{-1}}$ and by a thermal break aluminum frame with a *U-value* of 1 $\mathrm{W\,m^{-2}\,K^{-1}}$. Connections between elements are done in such a way that thermal bridges are avoided.

2.1.3. Integrated thermal-lighting simulations

The energy use for heating, cooling and artificial lighting has been determined by means of numerical simulations carried out by *EnergyPlus* software (EnergyPlus, 2011a). A typical meteorological year was chosen for each location and simulations were performed with a sub-hourly time-step (15 min). Occupancy and ventilation schedules, internal loads, temperature and illuminance set points were chosen according to best practice and internationally recognized sources (e.g. Owen, 2013) as well as international standards ("EN 15251:2008 – Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics," 2008). More information about these settings can be found in Goia et al. (2013), (Tables 1 and 2). Although *EnergyPlus* was primarily developed for simulating thermal loads and energy, it also incorporates (simplified) algorithms for daylight calculation (Split-Flux method, EnergyPlus, 2011b), which in turn allows artificial lighting energy use to be calculated.[3] Both research activities adopting EnergyPlus alone (e.g. Favoino et al., 2015; Singh et al., 2015) or in combination with other software for more accurate daylighting simulations (e.g. Huang et al., 2014) can be found in literature, supporting the suitability of this methodological approach to find an answer to the research questions.

2.2. Optimal WWR and numerical procedure

2.2.1. Objective function and data processing

In this paper, the optimal WWR value is defined as the value that minimizes, on an annual basis, the energy use for heating, cooling and artificial lighting. The objective function is given by Eq. (1), and E_{TOT} is calculated according to Eq. (2), where E_H is the energy use for heating, E_C is the energy use for cooling and E_L is the energy use for artificial light.

$$f : min\{E_{TOT}(\mathrm{WWR})\} \tag{1}$$

$$E_{TOT} = E_H + E_C + E_L \ \left[\mathrm{kW\,h_{PE}\,m^{-2}}\right] \tag{2}$$

In each group of simulations (see Section 2.2.3), the performance of the office building is computed five times, changing only the WWR value (in the range 0.20–0.80), and the corresponding E_H, E_C and E_L are assessed in terms of primary energy, using the conversion factor suggested by the Directive 2012/27/EU and set equal to 2.5 $\mathrm{kW\,h_{PE}\,kW\,h_{EE}^{-1}}$ (European Parliament, 2012).

The discontinuous function, $E_{TOT}(\mathrm{WWR})$, defined for five WWR values, is then turned into a continuous function in the range 0.20–0.80 by means of spline interpolation. A dedicated tool (based on a cubic equation) available in the *MatLab* environment was used to interpolate between two knots, imposing that the resulting $E_{TOT}(\mathrm{WWR})$ was continuous and differentiable in the entire domain (including the five knots), using not-a-knot conditions at the two extremes of the range. After such a procedure, it was therefore possible to find the minimum value over the entire range, which may correspond to WWR values that were not simulated.

The reason for adopting such a procedure is to limit the number of simulations, which is already relevant for single WWR, to few WWR values. The numbers of WWR simulated (five for each orientation) is, in the author's eyes, the minimum to reasonably cover the WWR range 0.20–0.80. A higher number of simulated WWR would have required a substantially higher computational time and data post-processing activity but just increased slightly the resolution of the $E_{TOT}(\mathrm{WWR})$ function.

2.2.2. Determination of activation flux for solar shading systems

The glazing systems of the office building façade integrated venetian blinds. The shading devices were displaced when there was a cooling load in the previous time-step of the simulation and when the solar irradiance in the time-step exceeded a certain value. The shading devices can be activated all year long, both in the heating and the cooling season. This strategy is a compromise between an approach that focuses only on the thermal aspect (based on cooling load check alone) and a strategy that uses an outdoor variable (solar flux check alone). It was chosen because it avoids venetian blinds being displaced when there is a cooling load caused by internal gain rather than by solar gain.

With such a strategy, the determination of the critical solar irradiance value that activates solar shading systems is not a straightforward procedure, since it is a function of the WWR. An optimal activation flux therefore needs to be determined for each WWR value (and for each orientation and climate). This procedure is integrated in the search for the optimal WWR value, as described in the following section, and the best activation flux was chosen each time from four different values (100, 200, 300 and 400 $\mathrm{W\,m^{-2}}$).

The best activation flux for each orientation and climate (see Section 3) are given in Table 2.

2.2.3. Workflow

The methodology adopted to determine the optimal WWR value for each of the four orientations of a single climate required a relatively high number of simulations. The

[3] Accuracy and limitations of *EnergyPlus* daylighting calculations are presented in Ramos and Ghisi (2010).

Table 2
Best activation flux for solar shading system, for each orientation and climate (in W m^{-2}).

WWR	South					North					West					East				
	0.20	0.35	0.50	0.65	0.80	0.20	0.35	0.50	0.65	0.80	0.20	0.35	0.50	0.65	0.80	0.20	0.35	0.50	0.65	0.80
Oslo	400 W m^{-2}	300	200	100	100	400	400	400	400	400	400	300	200	200	200	400	300	300	200	200
Frankfurt	400	200	200	200	100	300	300	300	300	300	400	300	200	200	200	400	300	200	200	200
Rome	400	200	200	100	100	400	400	400	400	400	400	400	200	200	200	300	300	200	200	200
Athens	400	300	200	200	100	400	400	400	400	400	400	300	200	200	200	400	300	200	200	200

sequence of simulations and data processing can be summarized and schematized in four steps as follows:

1. Simulation on a single orientation[4]
   20 simulations (4 activation fluxes for each of the 5 WWR values) for each orientation.
2. Best activation flux for shading system[4]
   Determination of the optimal activation flux for shading device displacement for each of the 5 WWR values, for each orientation, by means of Eq. (1) (choice of 100, 200, 300 and 400 W m^{-2}). Results are shown in Table 2.
3. Simulation on building (two façades)[5]
   25 simulations for couples (South–North/East–West) of façades (5 WWR values on front façade, 5 WWR values on back façade).
4. Optimal WWR[5]
   Determination of the optimal WWR value for a couple of façades (South–North/East–West) by means of Eq. (1) on continuous E_{TOT}(WWR) function.

The described workflow is then repeated for each climate and for each of the sensitivity analyses presented in the following section.

2.3. Sensitivity analysis

As mentioned, the aim of the research activity presented in this paper is to provide designers and researchers with ranges for WWR values that are sufficiently robust to (some) variations of design parameters and could therefore be used in a wide range of applications. For this reason, a sensitivity analysis was carried out by varying some parameters in order to understand how much the determined optimal value was reliable if used with (to some extent) different office buildings or equipment. The following parameters were considered: building compactness, building equipment efficiency and artificial light efficiency. It is important to mention that each parameter was investigated independently and combinations of two or more variations with respect to the base case were not considered. The results of the sensitivity analysis were later used to determine the WWR value ranges.

2.3.1. Building compactness – SA:V

The compactness of the building was changed while keeping constant the floor layout, the building structure and the width (14.4 m). This also means that the depth (5.4 m) of the cell office rooms was kept constant and the change in compactness of the building was achieved by increasing/decreasing the number of floors and cell office. A change in the depth of the building was not evaluated since this would probably result in a different plan concept or organization of the office spaces, and thus in a substantially different building. The fact that building compactness was changed without changing the depth of the cell office spaces influences the results of the analysis, since it is well known that the energy and environmental performance of a building is affected by the geometrical relation between the façade and depth of the space behind the façade – the deeper the building, the lower the influence of the façade configurations, among which the WWR parameter.

The SA:V parameter was used to assess the building compactness: the base case (Building 2) is characterized by a SA:V of 0.25 m^{-1}, while the other two simulated buildings had a SA:V equal to 0.20 m^{-1} and 0.30 m^{-1}. In Table 3, more details about the geometry of the three buildings can be found.

2.3.2. Building equipment efficiency – $SCOP_H$ and $SCOP_C$

Different versions of *Building 2* have also been simulated by changing the efficiency of the heating and cooling equipment in the range of −25% to +25%. This sensitivity analysis was aimed at assessing the impact of different efficiencies of HVAC components on the optimal façade configuration. Moreover, this type of analysis can give, to some extent, an indication of the optimal value of the WWR in the case of different internal gains (higher internal gain = less efficient cooling and more efficient heating components; lower internal gain = more efficient cooling and less efficient heating components). In Table 4, the adopted $SCOP_H$ and $SCOP_C$ for the base and other cases are displayed according to the different locations. It is worth noting that each simulation is made with just one variation from the base case, i.e. either more/less efficient heating or more/less efficient cooling equipment.

For the two warmest locations (see Section 3), simulations including night (free) cooling were carried out. Free

[4] Even when the simulation is meant to determine the activation flux for solar shading systems on a single orientation, the entire building is simulated. Steps 1 and 2 need to be repeated four times in each climate.

[5] Steps 3 and 4 need to be repeated twice in each climate to determine all four orientations, once with the building aligned along the south–north axis and once with the building aligned along the east–west axis.

Table 3
Dimension data of the three buildings used for the sensitivity analysis SA:V.

	SA:V (m^{-1})	Length (l) (m)	Width (w) (m)	Height (h) (m)	Office floors	Cell office rooms per floor
Building 1	0.20	53.3	14.4	96.9	27	14
Building 2	*0.25*	*45.9*	*14.4*	*28.9*	*8*	*12*
Building 3	0.30	38.5	14.4	18.7	4	10

Table 4
Values of seasonal COP in heating ($SCOP_H$) and cooling mode ($SCOP_C$) for the base case and for sensitivity analysis.

	$SCOP_H$			$SCOP_C$		
	Base case	+25%	−25%	*Base case*	+25%	−25%
Oslo	*2.4*	3.0	1.8	*4.0*	5.0	3.0
Frankfurt	*2.6*	3.3	2.0	*3.8*	4.8	2.9
Rome	*3.2*	4.0	2.4	*3.7*	4.6	2.8
Athens	*3.2*	4.0	2.4	*3.5*	4.4	2.6

cooling was activated when the outdoor air temperature was lower than the indoor air temperature but higher than 18 °C, and a ventilation rate of 6 ACH was adopted, together with the deactivation of the heat recovery system. In the sensitivity analysis with different equipment efficiencies, only simulations with a night cooling option were carried out for the two warmest locations.

2.3.3. Artificial light efficiency – η_L

In the reference case, a luminous efficacy of 100 lm W^{-2} was adopted. Simulations were also carried out with more or less efficient artificial lamps (in the range −25% to +25%, i.e. $\eta_L = 75$ lm W^{-2} and $\eta_L = 125$ lm W^{-2}, respectively) to evaluate the adoption of lighting systems characterized by different luminous efficacies.

2.4. Daylighting analysis

Daylight Autonomy (DA) (Taylor et al., 2006) and Useful Daylight Illuminance (UDI) (Nabil and Mardaljevic, 2005) metrics were used to assess the exploitation of natural light and risk of glare discomfort, respectively.

In particular, DA gives the percentage of the annual working time when the indoor illuminance set point (in this work, 500 lx) is met or exceeded, on spatial average, by natural light alone. As far as UDI is concerned, $UDI_{>2000}$ is adopted as an indirect, global indicator of glare risk. This metric measures the percentage of the annual working time when the (spatial average) daylight illuminance level is higher than 2000 lx.

Acceptable values for DA, showing a sufficient exploitation of natural light, should be higher than 50%. $UDI_{>2000}$ should be lower than 20%, while a value higher than that shows an increasing risk of glare discomfort. It is important to point out that glare discomfort is very much dependent on the geometrical relationship between the light source and the user. A detailed assessment of glare risk would thus require very detailed data (such as user/device positions and direction), which is not in line with the aim of the paper, i.e. to give indications that are valid for many cases and not for particular situations. For this reason, $UDI_{>2000}$ was chosen as a global risk indicator.

Daylighting analysis was used as a tool to verify whether or not the optimal WWR range also shows acceptable exploitation of natural light and sufficiently low glare risk.

3. Climates

The optimal WWR values were investigated in four different climates, evenly distributed across Europe so that they could represent the most common conditions of the continent and different latitudes. The Köppen–Geiger climate classification system (Peel et al., 2007) is herewith used to identify and select different climates. Details of the selected locations (Oslo, Frankfurt, Rome and Athens) can be found in Table 5. Typical meteorological years for the four locations were taken from the ASHRAE International Weather for Energy Calculations database.

Annual solar horizontal radiation presented in Table 5 is calculated as the sum of the hourly values of the global horizontal radiation. Heating and cooling degree-days are calculated as the sum of the daily average difference between the hourly outdoor air temperature and the base temperature (18 °C and 24 °C for heating and cooling degree-days, respectively).

Table 5
Different locations used for the simulations: climate classification and some key characteristics.

Location	Latitude	Köppen climate classification (Peel et al., 2007)	Climate description	Annual global solar horizontal radiation (kW h m^2)	Heating degree-days (T_{base} = 18 °C) (°C)	Cooling degree-days (T_{base} = 24 °C) (°C)
Oslo	59°57′ N	Dfb	Humid continental climate	879	4220	3
Frankfurt	50°07′ N	Cfb	Oceanic climate	1035	3131	36
Rome	41°54′ N	Csa	Hot-summer Mediterranean climate	1461	1505	123
Athens	37°58′ N	Csa	Hot-summer Mediterranean climate	1670	1155	326

A description of the four different locations and their climatic conditions is given below.

- *Oslo:* Dfb climate – Cold, without dry season, warm summer climate; in this climate, the cold season is the main concern for the building design, but summer outdoor air temperature and solar irradiance, especially if coupled with relatively high internal gain (typical in office buildings), can still lead to cooling energy need.
- *Frankfurt:* Cfb climate – Temperate, without dry season, warm summer climate; in this climate, both the cold and the warm season need to be addressed during the design stage since the energy needs for heating and cooling are often of the same order of magnitude.
- *Rome:* Csa – Temperate, dry and hot summer climate; in this climate, the summer season is the most complex from a building's energy point of view. This is especially true for office/commercial buildings, which are usually characterized by high internal heat gains; cooling energy use often far exceeds heating energy use in well-insulated buildings.
- *Athens:* Csa – Temperate, dry and hot summer climate too, but it just presents enough precipitation to avoid the BSh classification (arid steppe hot climate). This climate is more extreme and more southerly than Rome, and is thus characterized by higher solar horizontal radiation and cooling degree-days and lower heating degree-days. In this location, cooling energy use and accurate control of solar irradiation are crucial elements in the building's energy design.

4. Results

In the following Sections 4.1–4.4, the results of the simulations and sensitivity analysis are presented. For the sake of readiness, not all the diagrams related to the sensitivity

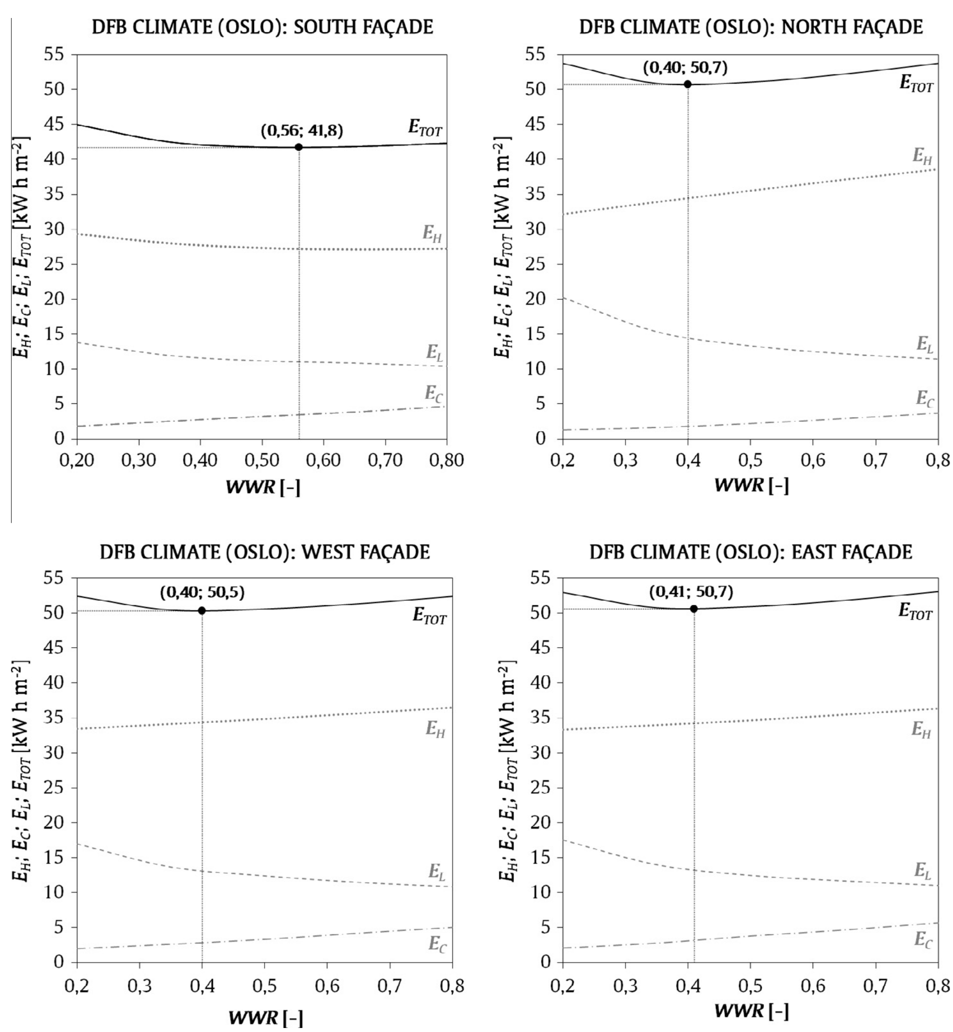

Fig. 1. Oslo – Dfb: E_{TOT}(WWR), E_H(WWR), E_C(WWR), E_L(WWR) and optimal WWR in the four main orientations.

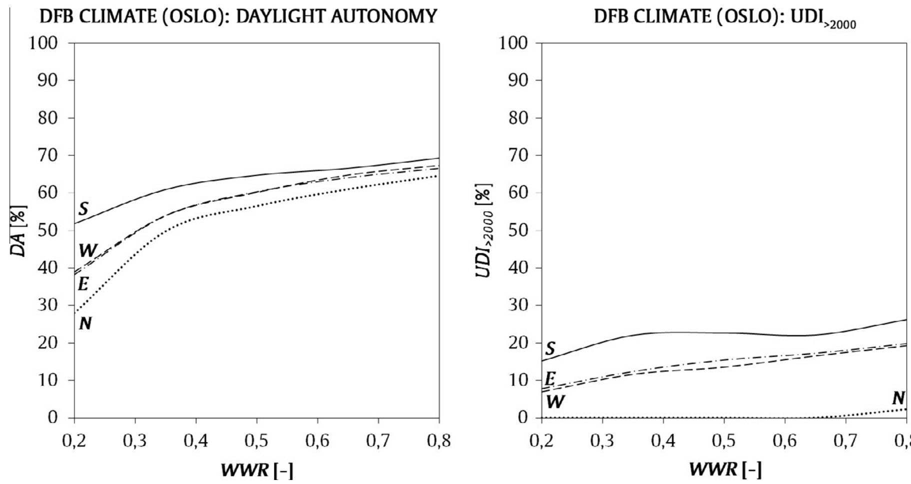

Fig. 2. Oslo – Dfb: DA(WWR) and $UDI_{>2000}$(WWR) in the four main orientations.

analysis are shown below, but they can be found in Appendix A. References to diagrams contained in Appendix A are made in the text, where necessary.

4.1. Oslo – Dfb

Optimal WWR values for the different orientations in Oslo are presented in Fig. 1, together with the values of E_H, E_C and E_L as a function of the WWR. The analysis of E_{TOT}(WWR), E_H(WWR), E_C(WWR) and E_L(WWR) shows that the optimization from a total energy perspective cannot be made just considering one (or even the main) energy demand, since E_H(WWR), E_C(WWR) and E_L(WWR) present different trends, and the optimal value of E_{TOT}(WWR) is given by the combined effect of the three elements.

The south-facing façade presents a behavior that is significantly different from that of the other three orientations. First of all, to some extent, it is possible to make use of solar passive heating (as shown by the fact that the heating energy use decreases as the WWR increases), while in the other three orientations it is impossible to reduce heating energy use by increasing the transparent area of the façade. Second, it is possible to highlight that high WWR values lead to a decrease in the artificial light energy use (a straightforward behavior), but the possibility to reduce artificial light energy use through a higher WWR is limited when compared to the other three orientations. North-, west- and east-facing façades present very similar trends and the optimal WWR values for those exposures are very close too (WWR of around 0.40). For all the orientations, the heating energy use is, as expected, the main aspect of the total energy balance, but it is worth highlighting that it is not the driving force for selecting the optimal WWR configuration.

The analysis of the daylighting conditions (Fig. 2) reveals that all four main orientations present a similar behavior, with increasing DA in line with increasing WWR (as expected), with a more significant increase in the range of 0.20–0.35; however, when the WWR is higher than 0.35, the increase in daylight exploitation is reduced. Moreover, it is possible to verify that, for the four optimal WWR values selected by minimizing E_{TOT}, DA is higher than 50%, showing a satisfactory exploitation of natural daylight. The south-facing façade shows a certain risk of glare discomfort where the $UDI_{>2000}$ is slightly higher than 20% in correspondence to the optimal WWR value – and in general around 20% in the entire WWR domain. The other three orientations do not present significant risk of glare discomfort, and the $UDI_{>2000}$ values are, for the optimal WWR configurations, well below 20%.

The output of the sensitivity analysis, presented in Table 3, reveals that the south-facing façade is characterized by the biggest sensitivity to a change in one of the variables investigated. However, it is important to note that the E_{TOT}(WWR) function is very close to a constant value in the range where optimal WWR value is found, regardless of the sensitivity analysis. This means that WWR values in the range 0.50–0.60 determine very similar E_{TOT}, which in turn means that, in practice, the exact WWR value (at least in the range 0.50–0.60) does not affect the energy use of the building. It is also possible to notice that a change in the SA:V, or in the $SCOP_H$/$SCOP_C$, or in η_L has a very similar impact in the range of values of WWR close to the optimal one, i.e. no variable determines a more noticeable change in the optimal WWR value.

A more detailed analysis, supported by the diagram presented in Appendix A (Fig. A.2), reveals that while a change in $SCOP_C$ has a bigger impact than that of $SCOP_H$ for the south-facing façade, the other three orientations show a mirrored behavior (a change of the $SCOP_H$ has a greater effect than that of the $SCOP_C$). As expected, more efficient cooling equipment allows higher WWR values to be adopted, and vice versa.

When different values of compactness (SA:V) are analyzed (Fig. A.1), the optimal WWR value moves toward

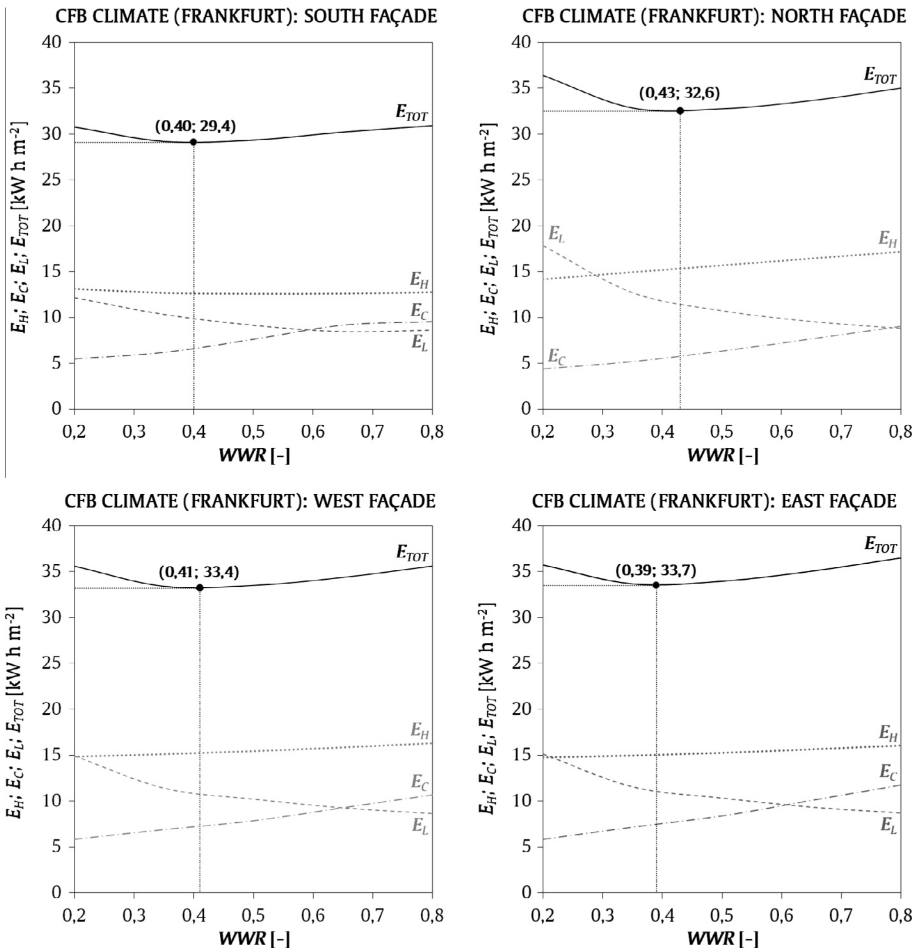

Fig. 3. Frankfurt – Cfb: E_{TOT}(WWR), E_H(WWR), E_C(WWR), E_L(WWR) and optimal WWR in the four main orientations.

lower values; this is due to an increased cooling energy use in the total energy balance as the building becomes more compact. The outcome of the analysis for different artificial lighting efficiency is conventional, showing that more efficient installation determines a move toward lower values of the optimal WWR due to a lower impact of the artificial lighting energy use in the total energy balance.

4.2. Frankfurt – Cfb

The first element to point out is that, contrary to the previous climate, E_H(WWR), E_C(WWR) and E_L(WWR) are in the same range of values, as shown in Fig. 3. As for Oslo's climate, there is not a single entry in the total energy balance that can be used as the driving force to determine the optimal WWR value (Table 7).

Table 6
Oslo – Dfb: optimal WWR values and corresponding DA and $UDI_{>2000}$ in the four main orientations; min. and max. optimal WWR values for different sensitivity analyses in the four main orientations.

	South		North		West		East	
Base case								
Optimal WWR	0.56		0.40		0.40		0.41	
DA (%)	66		53		57		58	
$UDI_{>2000}$ (%)	22		0		12		13	
	South		North		West		East	
Optimal WWR	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Sensitivity analysis								
SA:V	0.53	0.60	0.39	0.41	0.39	0.41	0.39	0.42
$SCOP_H$; $SCOP_C$	0.52	0.57	0.38	0.42	0.39	0.41	0.39	0.41
η_L	0.52	0.57	0.38	0.42	0.38	0.41	0.37	0.42

Table 7
Frankfurt – Cfb: optimal WWR values and corresponding DA and $UDI_{>2000}$ in the four main orientations; min. and max. optimal WWR values for different sensitivity analyses in the four main orientations.

	South		North		West		East	
Base case								
Optimal WWR	0.40		0.43		0.41		0.39	
DA (%)	65		60		63		62	
$UDI_{>2000}$ (%)	19		0		13		14	
	South		North		West		East	
Optimal WWR	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Sensitivity analysis								
SA:V	0.39	0.41	0.41	0.42	0.39	0.42	0.38	0.40
$SCOP_H$; $SCOP_C$	0.40	0.45	0.39	0.43	0.38	0.41	0.37	0.42
η_L	0.38	0.44	0.39	0.45	0.39	0.43	0.37	0.41

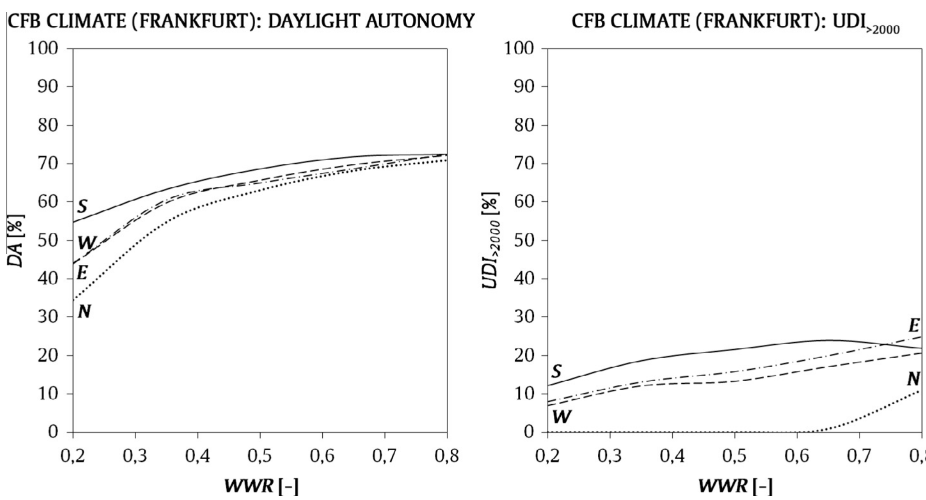

Fig. 4. Frankfurt – Cfb: DA(WWR) and $UDI_{>2000}$(WWR) in the four main orientations.

The analysis of the heating energy use as a function of the WWR reveals that passive solar heating is only possible in the south-facing façade in this climate too. However, due to the increased impact of the cooling load (which grows as transparency increases), the optimal WWR value for the south-facing façade is similar to that of the other three orientations, i.e. in the range of around 0.40. Contrary to the north-facing façade, where an increase in the WWR determines a non-negligible increase in the heating demand, E_H for east- and west-facing façades is barely influenced by the WWR configurations (higher WWR values, higher E_H). The impact of the WWR on the cooling energy demand increases when compared to the Dfb climate, especially for the east- and west-facing façades, with significantly higher values in the case of high values of WWR, and reaching values that are greater than those of the artificial light energy use.

Natural light exploitation (see Fig. 4) is similar to Oslo too (DA > 50% for all the orientations) and risk of glare discomfort is slightly reduced with $UDI_{>2000}$ values for optimal WWR a little lower than the corresponding figures in a Dfb climate. It is worth noting that the north-facing façade is the most sensitive to exploitation of daylighting: high values of WWR may halve E_L, compared to low WWR values.

A change in the efficiency of the cooling equipment has a wider impact on the optimal WWR value than a different efficiency of the heating equipment. Moreover, it is interesting to point out that a different efficiency of the heating installation does not change the shape of the E_{TOT}(WWR) function; rather, it just translates the function along the y-axis (see Fig. A.5). On the contrary, a change in the efficiency of the cooling equipment determines a different shape of the E_{TOT}(WWR) function, and, consequently, a more consistent shift of the best WWR (see Fig. A.5). As for the Nordic climate, the south-facing façade has the widest range for optimal WWR, followed by the north-facing façade and by the east and west orientations, which present a relatively narrow range.

When a different SA:V is used in the simulations, the optimal WWR moves toward lower values as the SA:V decreases (and the building compactness increases), as for the building located in Oslo. However, the impact of a different SA:V is lower compared to the northern location, especially for the south-facing façade. Such a

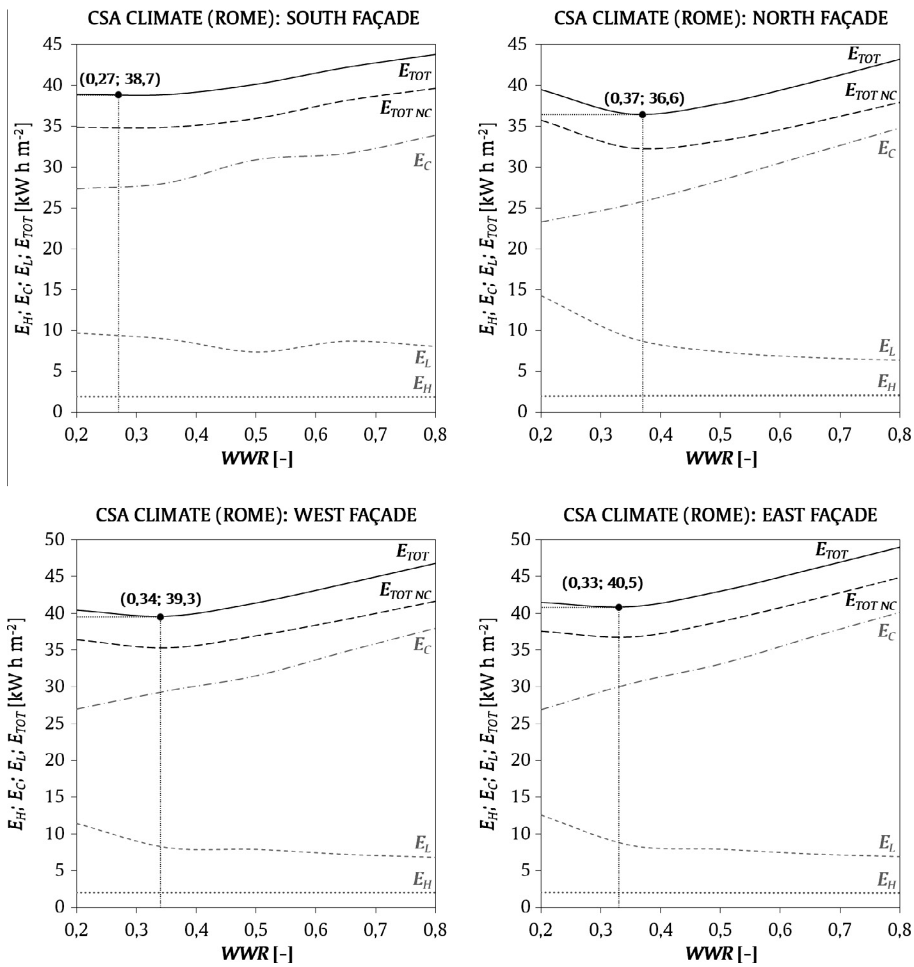

Fig. 5. Rome – Csa: E_{TOT}(WWR), E_{H}(WWR), E_{C}(WWR), E_{L}(WWR) and optimal WWR in the four main orientations.

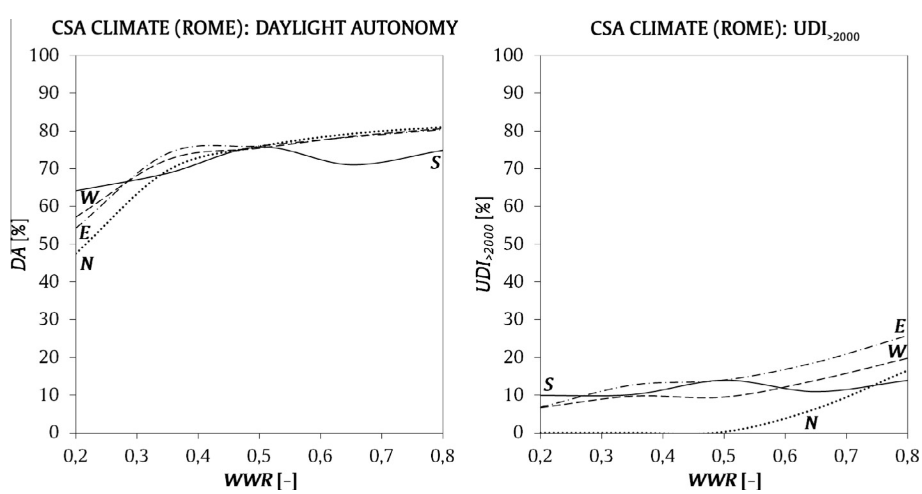

Fig. 6. Rome – Csa: DA(WWR) and $\mathrm{UDI}_{>2000}$(WWR) in the four main orientations.

behavior is probably due to the higher cooling energy demand in the Cfb climate even with a relatively non-compact building, which in turn leads to a lower influence of the building's shape on the E_{TOT}(WWR).

The analysis of the influence of different efficiencies of the artificial lighting equipment follows that of the Oslo climate and it is not repeated here for the sake of brevity.

4.3. Rome – Csa

Similar to previous results, the simulations of the building located in Rome confirm that, except for the south-exposed façade, optimal WWR values cannot be found just by looking at one aspect of the total energy balance even in a much more southerly location and warmer climate.

Table 8
Rome – Csa: optimal WWR values and corresponding DA and $UDI_{>2000}$ in the four main orientations; min. and max. optimal WWR values for different sensitivity analyses in the four main orientations.

	South		North		West		East	
Base case								
Optimal WWR	0.27		0.37		0.34		0.33	
DA (%)	67		70		71		73	
$UDI_{>2000}$ (%)	10		0		10		12	
	South		North		West		East	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Sensitivity analysis								
SA:V	0.20	0.34	0.36	0.37	0.32	0.34	0.32	0.34
$SCOP_H$; $SCOP_C$	0.27	0.34	0.36	0.40	0.32	0.36	0.30	0.36
η_L	0.25	0.33	0.36	0.39	0.31	0.35	0.28	0.35

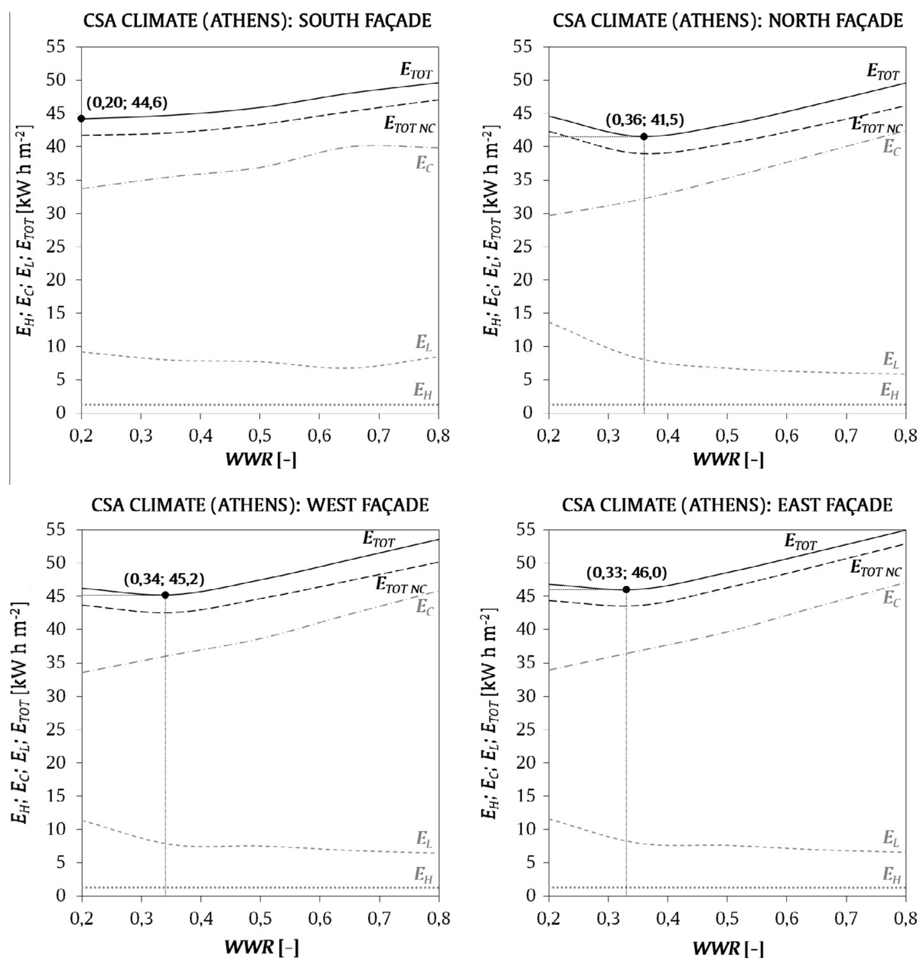

Fig. 7. Athens – Csa: E_{TOT}(WWR), E_H(WWR), E_C(WWR), E_L(WWR) and optimal WWR in the four main orientations.

The south-facing façade is an exception to this rule, showing that the best WWR (for the base case) is that where the cooling energy use is minimized. In this climate and for this orientation, the cooling energy use is the most relevant entry: it increases as the transparent percentage increases (Fig. 5), and it is the driving force of the energy balance. Other orientations still present a very relevant impact of E_C, but the optimal solution is found as the best combination of cooling and artificial lighting energy use. In this respect, it is worth noting that heating energy use is constant over the entire WWR domain, so it does not affect the search for the best transparent percentage. The optimal WWR value is in the lower range of the investigated domain (WWR = 0.27), and it still presents an acceptable exploitation of natural light (DA = 67%) with low risk of glare discomfort, as shown in Fig. 6 and Table 8.

It is worth commenting that DA(WWR) for the south-facing façade show an optimal WWR of around 0.50, which is not an expected behavior. This is probably due to the selected activation flux for the solar shading system

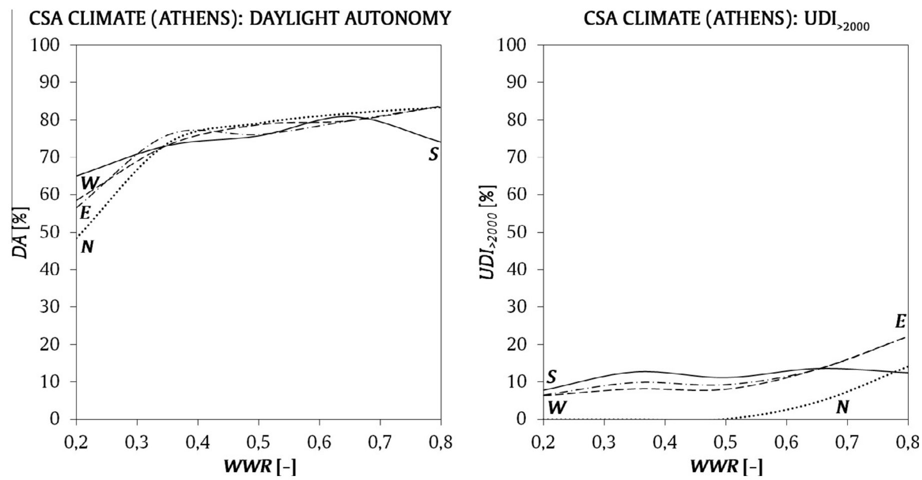

Fig. 8. Athens – Csa: DA(WWR) and $UDI_{>2000}$(WWR) in the four main orientations.

(which depends on the WWR and is optimized considering thermal energy only, as previously explained), which determines a nonlinear trend in the DA(WWR).

North-, east- and west-facing façades present very similar behavior, and the configuration that minimizes the total energy use is found in the range 0.33–0.34 (east- and west-facing façades) and around 0.37 (north-facing façade). None of the orientations shows low utilization of natural light (even for very low WWR values) and risk of glare discomfort is only noticeable for high WWR configurations of the east- and west-facing façades.

For the building located in Rome, a night cooling strategy has also been applied. The results (dashed line $E_{TOT\ NC}$(WWR) in Fig. 5) show that free cooling does not affect the optimal WWR but translates the E_{TOT}(WWR) toward lower values, with a very similar effect for all the orientations.

The outcome of the sensitivity analysis reveals good stability of the optimal WWR configuration when there is a change in the SA:V (Fig. A.7) for the north-, east- and west-facing façades. In contrast, the south-facing façade is quite sensitive to different compactness, with the optimal configuration ranging from 0.20 to 0.34 (the latter in the case of not very compact buildings).

Robustness to different efficiencies of the heating and cooling equipment is relatively high for north- and west-facing façades, and lower for east- and south-facing façades. In all cases, the cooling equipment efficiency (Fig. A.8) leads to the biggest change in the optimal configuration. A change in the heating equipment efficiency does not significantly affect the optimal WWR, nor the $E_{TOT\ NC}$(WWR). This is because the E_H is very low compared to the other aspects of the total energy balance and thus a (small) change in its value has little impact on the total energy use.

As for the previous two locations, the sensitivity analysis for the artificial light equipment returns quite conventional results, showing that this variable has, in general, a moderate impact on the optimal WWR value, with a larger impact for east- and south-facing façades.

4.4. Athens – Csa

The results and analysis of the search for optimal WWR values (Table 9) in the warmest climate are similar to those of the simulations carried out for Rome. As expected, this location shows a higher total energy use, mostly due to a greater cooling energy use.

Table 9
Athens – Csa: optimal WWR values and corresponding DA and $UDI_{>2000}$ in the four main orientations; min. and max. optimal WWR values for different sensitivity analyses in the four main orientations.

	South		North		West		East	
Base case								
Optimal WWR	0.20		0.36		0.34		0.33	
DA (%)	65		74		73		75	
$UDI_{>2000}$ (%)	8		0		8		7	
	South		North		West		East	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Sensitivity analysis								
SA:V	0.20	0.27	0.36	0.37	0.32	0.34	0.31	0.33
$SCOP_H$; $SCOP_C$	0.20	0.33	0.36	0.39	0.33	0.36	0.31	0.35
η_L	0.20	0.20	0.35	0.38	0.32	0.35	0.31	0.34

Table 10
Maximum increase in total energy use in case of non-optimal selection of WWR for the different climates and orientations. Information is also visually communicated using a scale of background color (light gray: very small increase, i.e. ⩽5%; green: small increase, i.e. 6–10%; orange: medium increase, i.e. 11–15%; red: large increase, i.e. >16%).

	South		North		West		East	
max ΔE_{TOT}(WWR) (%)	8		6		4		5	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
OSLO – Dfb								
SA:*V* (%)	7	9	5	8	3	5	4	6
$SCOP_H$; $SCOP_C$ (%)	7	9	4	9	4	5	5	6
η_L (%)	7	9	8	8	5	6	6	6
	South		North		West		East	
max ΔE_{TOT}(WWR) (%)	6		12		7		9	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
FRANKFURT – Cfb								
SA:*V* (%)	5	8	9	15	6	9	7	11
$SCOP_H$; $SCOP_C$ (%)	6	8	10	14	7	9	6	11
η_L (%)	7	8	10	15	9	9	9	11
	South		North		West		East	
max ΔE_{TOT}(WWR) (%)	13		19		18		20	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
ROME – Csa								
SA:*V* (%)	11	17	16	21	15	22	17	24
$SCOP_H$; $SCOP_C$ (%)	11	16	14	21	15	21	19	25
η_L (%)	12	14	16	21	17	20	18	22
	South		North		West		East	
max ΔE_{TOT}(WWR) (%)	13		19		19		19	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
ATHENS – Csa								
SA:*V* (%)	8	17	17	22	15	22	16	23
$SCOP_H$; $SCOP_C$ (%)	11	14	16	21	16	20	19	24
η_L (%)	11	13	17	21	17	20	18	21

Table 11
Suggested WWR range values for different climates and orientations that can be used in the preliminary stage of design. Information is also visually communicated using a scale of background color (light gray: very small increase, i.e. ⩽5%; green: small increase, i.e. 6–10%; orange: medium increase, i.e. 11–15%; red: large increase, i.e. >16%).

	South	North	West	East
OSLO – Dfb				
Suggested WWR range	0.50–0.60	0.37–0.43	0.37–0.43	0.37–0.43
	South	North	West	East
FRANKFURT – Cfb				
Suggested WWR range	0.37–0.45	0.40–0.45	0.37–0.43	0.37–0.43
	South	North	West	East
ROME – Csa				
Suggested WWR range	0.25–0.35	0.35–0.40	0.30–0.35	0.30–0.35
	South	North	West	East
ATHENS – Csa				
Suggested WWR range	0.20–0.30	0.35–0.40	0.30–0.35	0.30–0.35

Compared to Rome, no significant reductions are seen as far as the artificial lighting use and heating energy use are concerned (both are just slightly lower than in Rome). The effectiveness of a night cooling strategy has been evaluated in this climate too and results (Fig. 7) are in line with those in Rome: there is a reduction in E_{TOT}(WWR) but no impact on the best transparent percentage. The optimal WWR value for each of the four main the orientations is very similar to the correspondent one in Rome and the analysis of the visual environment follows that of the Italian site: relatively high values of DA and acceptable values of $UDI_{>2000}$ (see Fig. 8).

The optimal WWR value for the south-exposed façade is the lowest value of the investigated WWR range (0.20). Only with a less compact building (SA:V = 0.30) and with more efficient cooling equipment can the optimal transparent percentage increase (see Figs. A.10 and A.11), with the highest optimal WWR value equal to 0.33. It is worth mentioning that a change in the luminous efficacy of the installed lights does not affect the optimal solution.

Results for north-, east- and west-facing façades are almost identical to those obtained for Rome, with the same optimal WWR values but higher corresponding E_{TOT} and $E_{TOT\ NC}$. The outcome of the sensitivity analysis reveals an even lower sensitivity of the optimal transparent percentage to a change in the cooling equipment than in Rome (and a change in the heating equipment has no impact at all), very little influence of the compactness of the building (as usual, the more compact the building, the lower the optimal WWR) and a moderate impact from the artificial lighting equipment – with even smaller implications than in Rome.

5. Discussion

The results presented in this paper show that it is possible to find an optimal WWR value, which is not a trivial one, that minimizes the sum of energy use for heating, cooling and lighting (*Q.1*). Each orientation and climate requires a dedicated optimal transparent percentage, though it has been shown that the optimal WWR range is rather limited across very different climates, and especially for some orientations.

Using a sensitivity analysis, robustness of optimal WWR values has been tested against different values of some variables that might be unknown at the very early stage of the building design process, such as efficiency of the HVAC and of the artificial lighting equipment, or the compactness of the construction (*Q.2*).

Results show that HVAC efficiency can, sometimes, cause a rather significant change in the optimal WWR value, and the efficiency of the cooling system is the most relevant between $SCOP_H$ and $SCOP_C$. A change in the luminous efficacy of the adopted lamps presents a standardized output, regardless of the locations and orientations: the more efficient the artificial lighting system, the lower the optimal WWR. A similar result is seen by analyzing the influence of the building compactness: more compact buildings need lower values of WWR (since cooling energy use increases), and less compact constructions should adopt more transparent façades.

A remark is necessary to point out that the investigation reveal that conventional ways of thinking (e.g. use small windows on the north orientation and larger window on the south orientation) are not always true when it comes to combined consideration of heating, cooling and lighting, in presence of dynamic features of the glazing systems (in this case an integrated solar shading system). It is shown that total energy can be non linearly dependent of the WWR and that, when taking one entry of the energy balance at a time without considering the total picture, one might find a non-optimal configuration.

When it comes to the analysis of the implication of the WWR on the luminous environment and the impact on the daylight autonomy and the useful daylight illuminance, the investigation shows a general, reasonable trend (an increase in the WWR determines a better exploitation of daylighting an a higher risk of glare discomfort). However, there are particular cases (in warm-dominated climates, for south façades) where the maximum DA is not achieved in combination with the largest WWR and the highest values for $UDI_{>2000}$ are recorded for WWR around 0.5. This fact can be explained considering the combined effect of WWR and activation solar flux for shading system – in those cases, the solar gain and the transmitted visible radiation were higher for smaller windows with higher activation flux than for larger windows with lower activation flux. This explanation is supported by the analysis of the E_C(WWR) curves, which are not always linearly dependent on the WWR but present maximums in correspondence of intermediate WWR values.

The search for the optimal transparent percentage has also shown that the impact of the WWR configuration on the total energy use is rather limited, or at least less relevant than suggested in previous research. This outcome is directly related to research question *Q.3*, which deals with the potential for energy use reduction when the best configuration is chosen instead of another (or the worst) one. In order to evaluate this influence, the maximum increase in total energy use for non-optimal WWR – *max* ΔE_{TOT}(WWR) [%] – has been defined and calculated according to Eq. (3):

$$max\ \Delta E_{TOT}(\mathrm{WWR}) = 100 \cdot \frac{max\{E_{TOT}(\mathrm{WWR})\} - min\{E_{TOT}(\mathrm{WWR})\}}{min\{E_{TOT}(\mathrm{WWR})\}}\ [\%] \quad (3)$$

which gives the increase in the energy use when the worst WWR configuration is used in place of the best, and is thus considered the worst-case scenario. Results from this analysis, on both the base case and cases analyzed in the sensitivity analysis, are presented in Table 10. Façade orientations in different climates are also categorized in four classes, highlighted with different colors: gray (when $max\ \Delta E_{TOT}(\mathrm{WWR}) \leqslant 5\%$), green (when $5 < max\ \Delta E_{TOT}(\mathrm{WWR}) \leqslant 10\%$), yellow (when $10 < max\ \Delta E_{TOT}(\mathrm{WWR}) \leqslant 15\%$) and red (when $max\ \Delta E_{TOT}(\mathrm{WWR}) > 15\%$).

It is possible to see that for façades located in cold-dominated or more balanced climates (Dfb and Cfb), the adoption of a wrong WWR is less critical than in warm-dominated climates. East- and west-facing façades in Oslo show a *max* ΔE_{TOT}(WWR) that is lower than 5%, while south- and north-facing façades present a slightly higher value, though still quite a low one. It is worth mentioning that the highest increase in energy use for the south-facing façade is seen when a low value of WWR is used – even highly transparent façade solutions seem to be acceptable and energy-efficient.

In Frankfurt, the north-facing façade is the most sensitive to a change in the WWR configuration, with a maximum increase in energy use (in relation to a WWR of 0.80) of 12%, followed by the east-facing façade (9%), west- and south-facing façades (7% and 6%, respectively). In this climate, the highest increases in energy use are seen when either a low or a high WWR value is adopted – in detail, the north-facing façade should particularly avoid low WWR values, while south-, east- and west-facing façades should not have WWR values at either extremes of the analyzed WWR domain.

The impact of the WWR increases as the location moves southwards, with Rome and Athens showing very similar values. For both the locations, contrary to what common sense would suggest, the south-facing façade is not the most critical one. This is probably because the energy balance of the south-facing façade is so dominated by solar irradiance that an appropriate activation of shading devices (which differs according to the WWR) is capable of preventing a high increase in the energy use, even if very large glazed surfaces are used. In contrast, the energy balance of the east-facing façade, immediately followed by the west- and north-facing façades, is the most sensitive to the use of non-optimal WWR, with a potential increase in total energy use of up to 25% (when high values of WWR are adopted).

Based on the results presented in Tables 6–9, it is possible to define a WWR range for each location and orientation that guarantees, within the boundary conditions set in this investigation, to be close enough to the best transparent percentage value (*Q.4.*) so that a very good energy performance can be achieved. In Table 11, the suggested values are reported and the same classification (from gray to red) is used to highlight which orientations are the most and the least sensitive to a non-optimal WWR value. This information is resumed graphically in the graphical highlight of the article.

6. Limitations and future works

The investigation discussed in this paper presents some limitations that are worth discussing and might be considered for a future development of this research activity.

First of all, the technology of the glazed unit (and of the opaque wall) is kept constant regardless of the climate. This choice was made to reduce the numbers of simulations, which would have increased significantly if different combinations of opaque/transparent *U-values* and SHGC had to be tested. The technologies of the building envelope components and installations adopted in this investigation are among the best available on the market today and should be seen as the reference ones in the very next future. However, one might argue that the use of a triple glazed unit in a warm climate can be excessive, as well as highly insulated opaque walls might not be necessary. Test simulations have been carried out during the research activity and have proved that lowering the thermal resistance of the building envelope results in an increase in the total energy use of the building, even if it is located in a warm climate, and even considering the combination of heating and cooling energy use. This occurs because solar gains through the transparent building envelope can be efficiently managed thanks to the shading system and it is not really possible to count on the heat loss through the building envelope components to reduce the cooling load in summer – acting with ventilation, either natural or mechanical, is a much more effective strategy.

For all these reasons the investigation has been limited to a highly insulated building envelope, in combination with a relatively highly transparent glazing system equipped with a dynamic shading system. Results are therefore valid only under these conditions.

Second, only one particular type of office building was investigated, whose plan layout has a central corridor with cell office rooms on both the sides, building services, staircase and lifts at the two ends of the corridor. Other types of office building with different layouts (e.g. with double corridor, or with an atrium structure) could present SA:V values similar to those investigated in this activity, but have features and geometrical relation between the façade and the indoor environment that could lead to different results.

However, the type of office building chosen as case-study in this research is among those with the minimum room depth – and thus among those where the influence of the façade on the energy and environmental performance of the building is higher. The case study was indeed chosen because of this characteristic, so that the impact of the WWR configuration could be assessed under the most relevant conditions.

Third, "ideal" users were supposed, i.e. occupants do not interact with the control of shading systems, temperature set points and ventilation rates, and the occupancy schedule was set during the optimization process. Moreover, a certain set of occupancy schedules and other variables were adopted, and though derived from well recognized standards (Owen, 2013), several different combinations might have been chosen.

A future development of the research activity might be oriented toward testing the robustness of the optimal WWR against, and assessing the possible increase in energy use due to, non-optimal operations or different schedules, set points or other control logics that differ from those implemented during the search for the optimal WWR.

Fourth, a particular aspect that it is worth future investigations is the logics for activation of the solar shading system integrated in the façade. The investigation presented in this paper is based on a strategy that is a compromise between an approach that focuses only on the indoor environmental thermal aspect and one that uses an outdoor environmental variable. Several other strategies might have been investigated (among which, some base on variables related to the luminous environment), but preliminary simulations during the investigation had shown that the selected strategies is the one leading to the lowest total energy use. Furthermore, different strategies could be selected during the different seasons of the year, or different activation values selected (e.g. a different activation flux between winter and summer).

A research activity aimed at deepening the correlation between strategies for solar shading systems activation, total energy use and WWR could provide a good complementary knowledge to the one presented in this article and would establish new rule of thumbs (or confirm these) also in case of different strategies for controlling shading systems.

Fifth, the search for the optimal transparent percentage has only been carried out for a few (representative) locations and climates. In future, correlations between the optimal WWR and climate-related variables (such as solar irradiation and degree-days) can be investigated based on data presented in this paper in order to determine empirical correlations that allow the evaluation of the optimal WWR to be carried out starting from climate data.

7. Conclusion

By means of an extensive number of integrated thermal-lighting simulations, coupled with a sensitivity analysis, suggested ranges for the WWR around the optimal WWR value have been found for different climates and orientations, for a particular type of office building (single corridor layout with cell office rooms), equipped with state of the art technologies for building envelope components (including shading systems) and installations.

Most of the optimal WWR values are found in a relatively narrow range, i.e. $0.30 < \text{WWR} < 0.45$, even for buildings placed in very different climates. The south-facing façade shows a larger variability, as the optimal transparent percentage can be as high as 0.60 in very cold climates (Dfb) and as low as 0.20 in very warm climates (Csa). A somehow surprising conclusion is that the south-facing façade is not the most critical one as far as the selection of optimal WWR is concerned (if suitable shading strategies are adopted): a wrong selection of the WWR in north-, east- and west-facing façades in a warm climate can cause a higher increase in the total energy use (up to +25%) than in a south-facing façade. East- and west-facing façades in cold climates are those where a non-optimal transparent percentage causes the lowest increase in energy use (as low as +5%).

The investigation also highlights that, for almost all the orientations and locations (south-facing façades in Rome and Athens are the only exceptions), the determination of the optimal WWR value requires the contemporary evaluation of heating, cooling and lighting energy use, and focusing on just one (or two) entry(ies) of the total energy balance is not enough nor correct, and may lead to wrong conclusions.

Looking at the results from a climate comparative perspective, the investigation pointed out that more transparent building envelopes are recommended moving toward colder climates. This is a very clear and reasonable indication that may appear to be in disagreement with the still well-spread "rule-of-thumb" that suggests to have small windows in cold climates – a rule developed with the focus placed only on the energy use for heating. The outcome is also confirmed by the fact that for almost all the locations (excluded Oslo, the coldest climate) the north-exposed façade is the one where the optimal WWR has the highest value.

This fact can be explained knowing that all the energy uses (including for artificial lighting) were considered in the analysis, and that the glazing technologies adopted presented high-performance thermal resistance.

The investigation also pointed out that warm-dominated climates are those where the choice of a suitable WWR value is more critical, since a WWR value far from the optimal range leads to the highest increase in energy use (due to the increase in the energy use for cooling). Finally, it is worth noting that the research outcome shows that the façade configuration (in this case, the WWR) has a lower impact on the total energy use of the building when compared to previous studies. This is because the efficiency of the entire construction has increased so much in the last few decades that each subsystem has been optimized and its impact on the overall energy use becomes more limited. This happens even if the office building adopted in this research (single corridor layout with cell office rooms) presents a limited depth of the indoor environment compared to other typologies, and it is thus a case where the influence of the façade on the energy and environmental performance of the building is higher.

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Appendix A

See Figs. A.1–A.12.

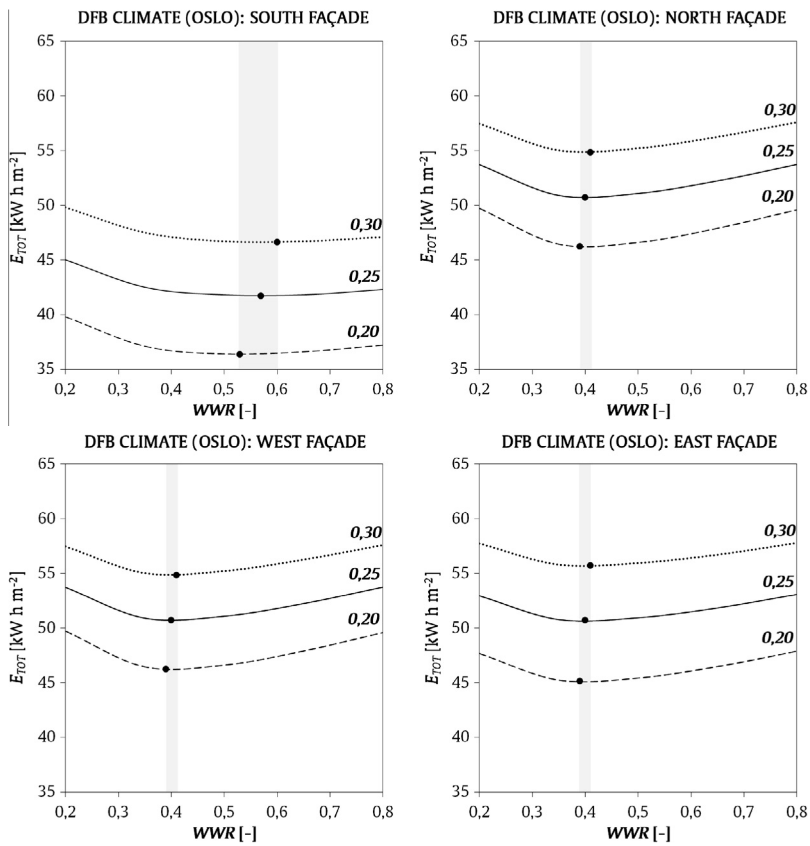

Fig. A.1. Oslo – Dfb: E_{TOT}(WWR) and optimal WWR for different SA:V values in the four main orientations.

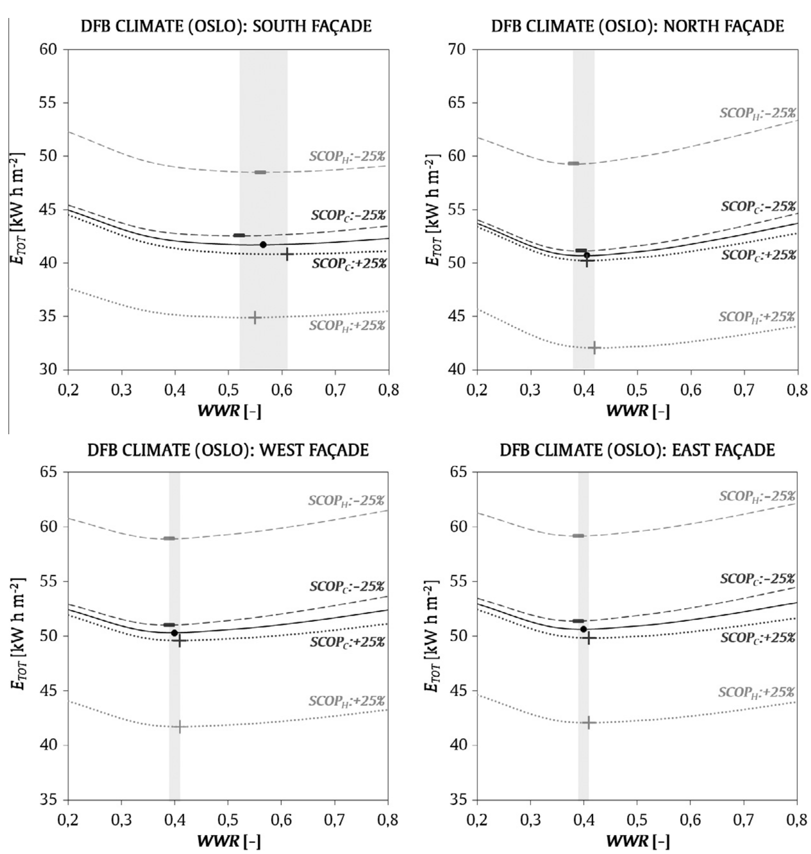

Fig. A.2. Oslo – Dfb: E_{TOT}(WWR) and optimal WWR for different $SCOP_H$ and $SCOP_C$ values in the four main orientations.

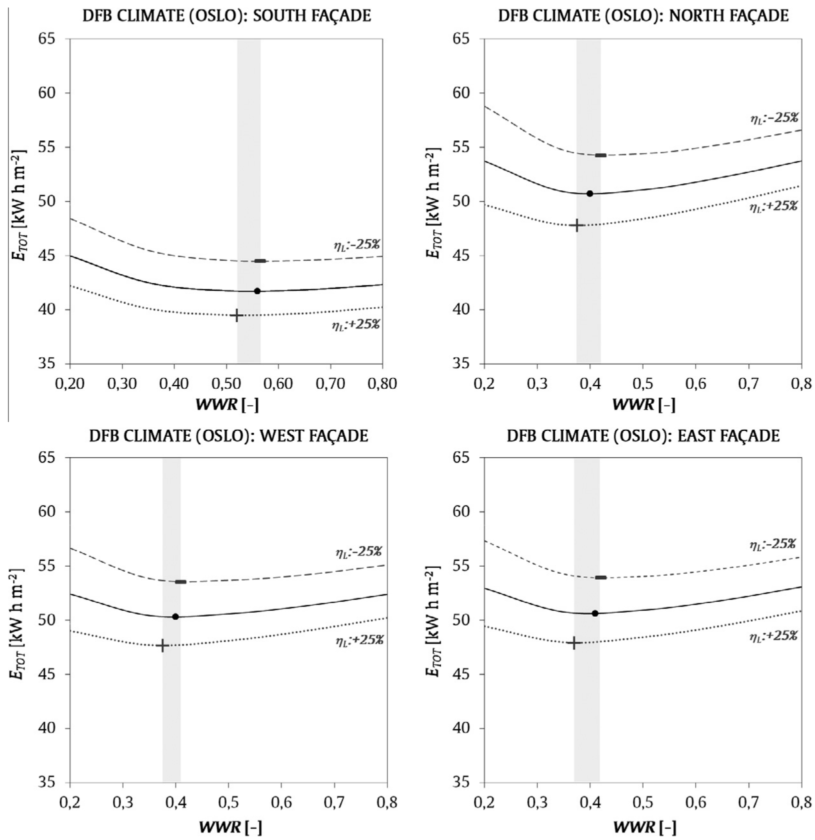

Fig. A.3. Oslo – Dfb: E_{TOT}(WWR) and optimal WWR for different η_{L} values in the four main orientations.

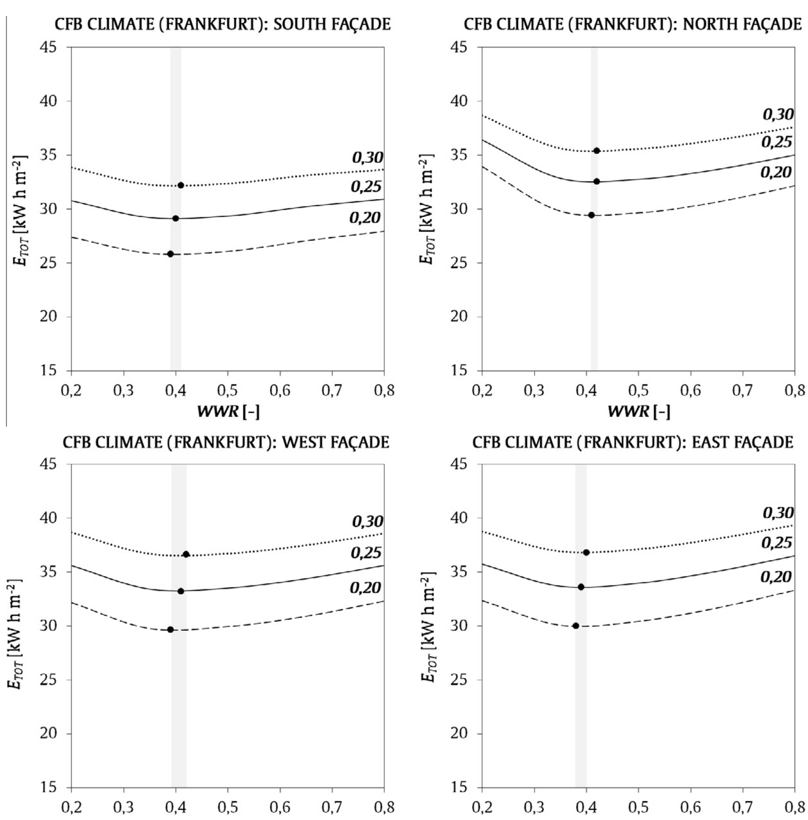

Fig. A.4. Frankfurt – Cfb: E_{TOT}(WWR) and optimal WWR for different SA:V values in the four main orientations.

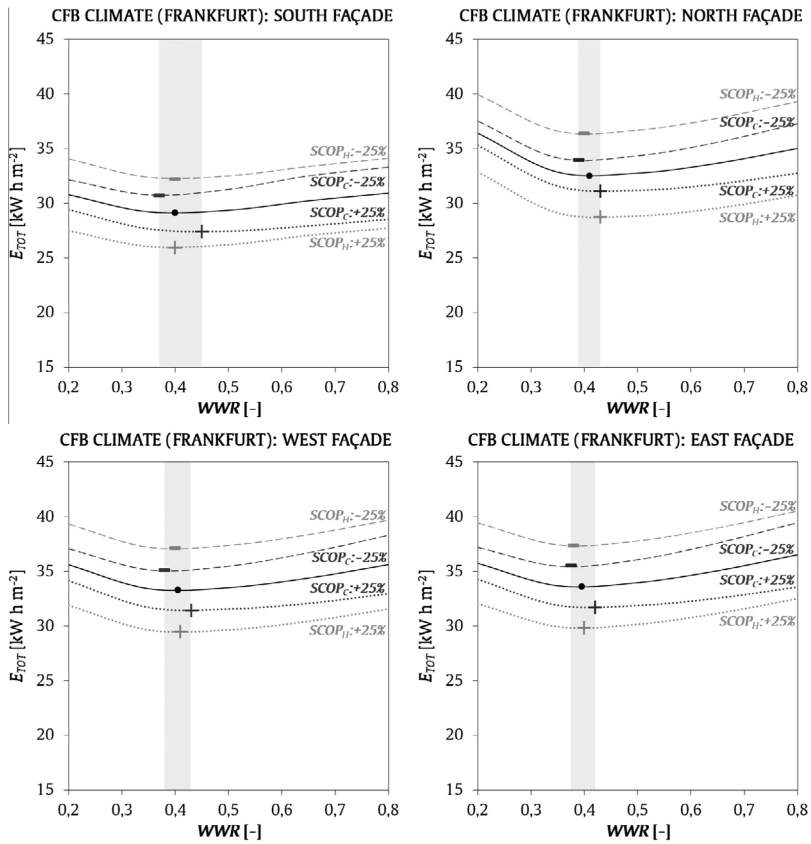

Fig. A.5. Frankfurt – Cfb: E_{TOT}(WWR) and optimal WWR for different $SCOP_H$ and $SCOP_C$ values in the four main orientations.

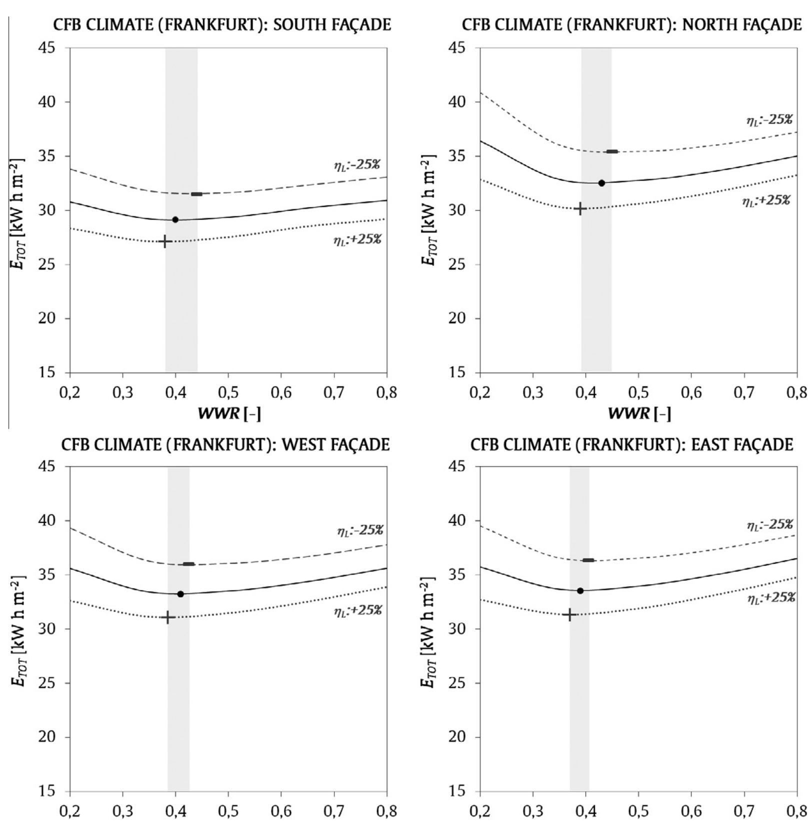

Fig. A.6. Frankfurt – Cfb: E_{TOT}(WWR) and optimal WWR for different η_L values in the four main orientations.

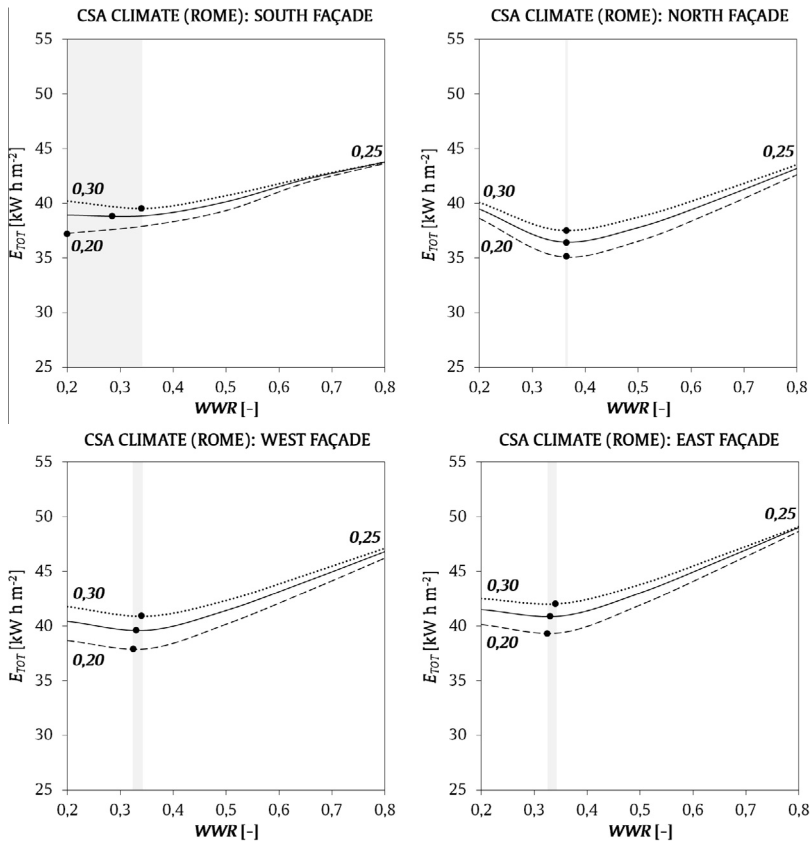

Fig. A.7. Rome – Csa: E_{TOT}(WWR) and optimal WWR for different SA:V values in the four main orientations.

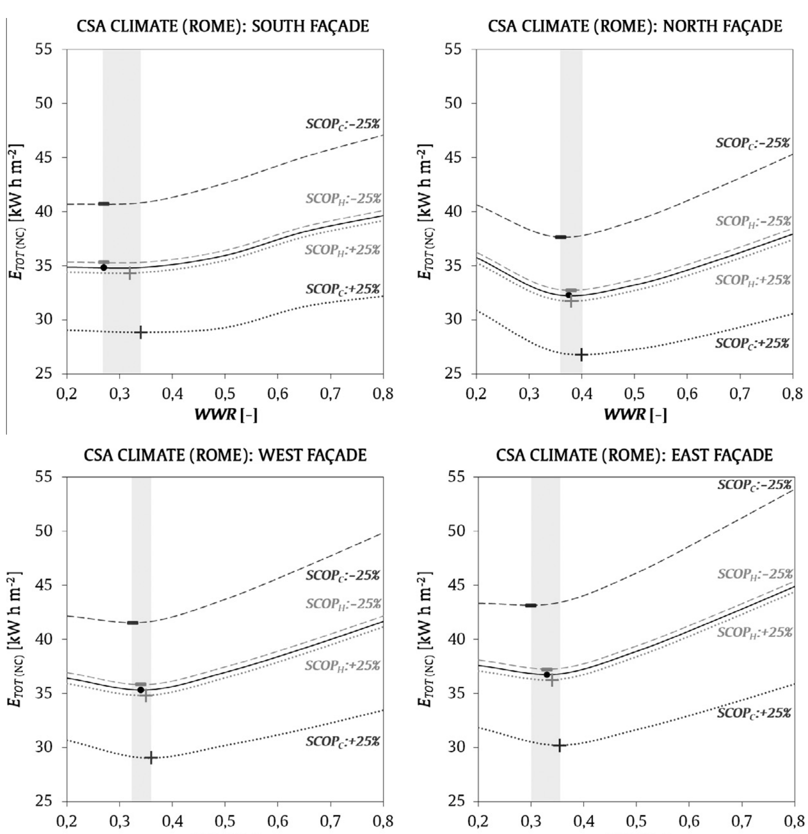

Fig. A.8. Rome – Csa: E_{TOT}(WWR) and optimal WWR for different $SCOP_H$ and $SCOP_C$ values in the four main orientations.

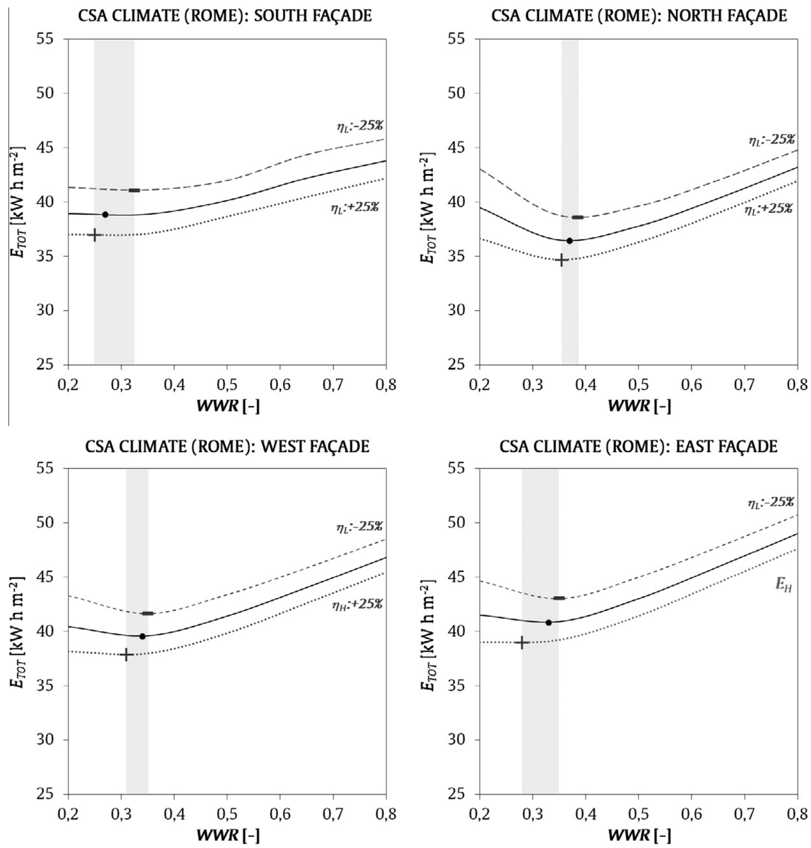

Fig. A.9. Rome – Csa: E_{TOT}(WWR) and optimal WWR for different η_L values in the four main orientations.

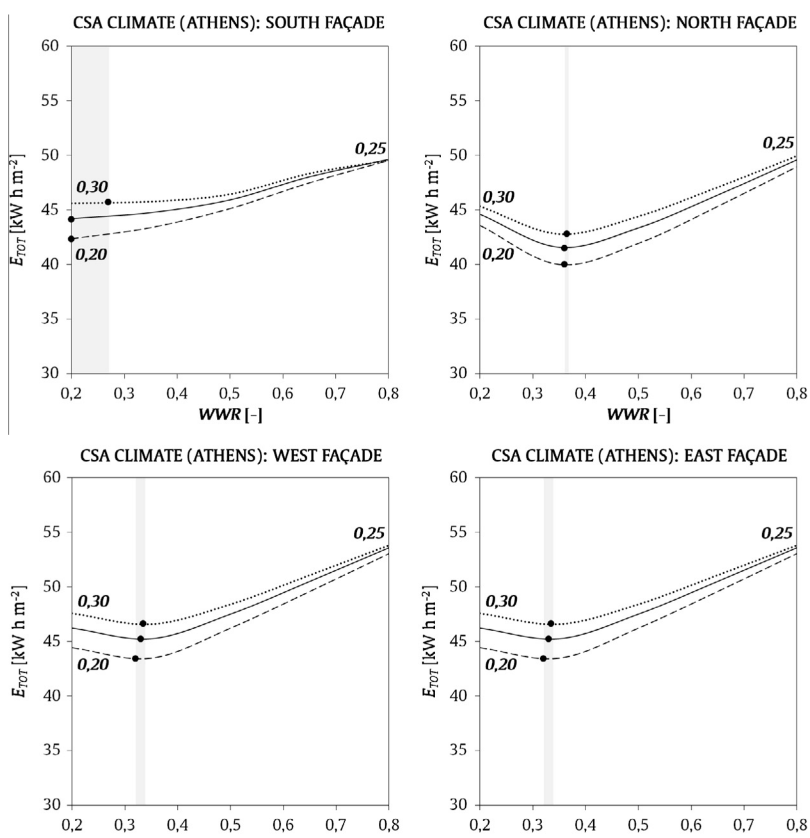

Fig. A.10. Athens – Csa: E_{TOT}(WWR) and optimal WWR for different SA:V values in the four main orientations.

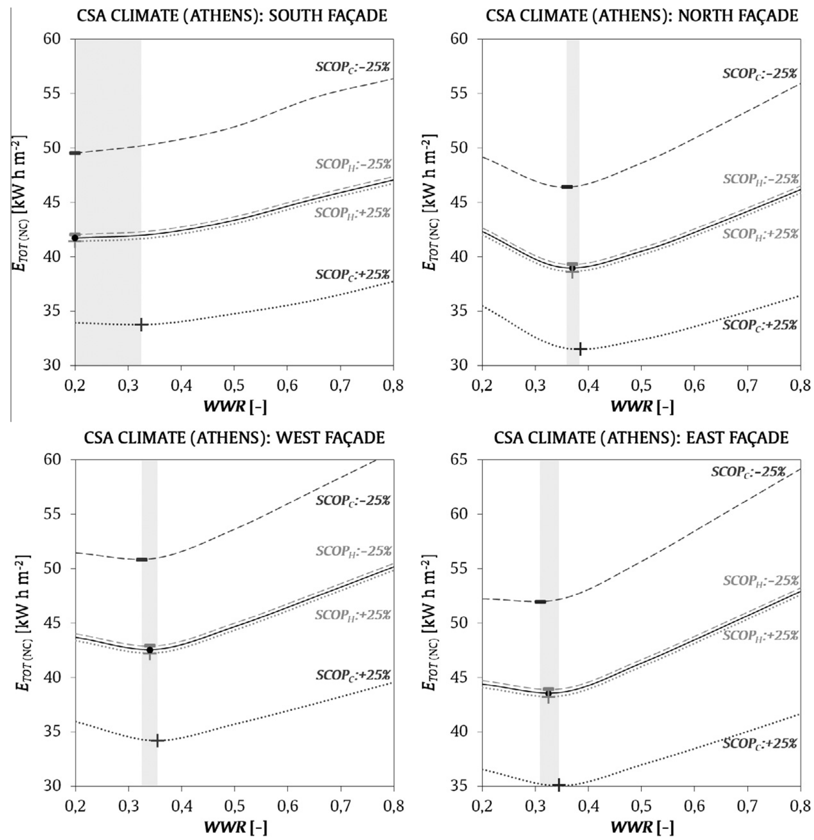

Fig. A.11. Athens – Csa: E_{TOT}(WWR) and optimal WWR for different $SCOP_H$ and $SCOP_C$ values in the four main orientations.

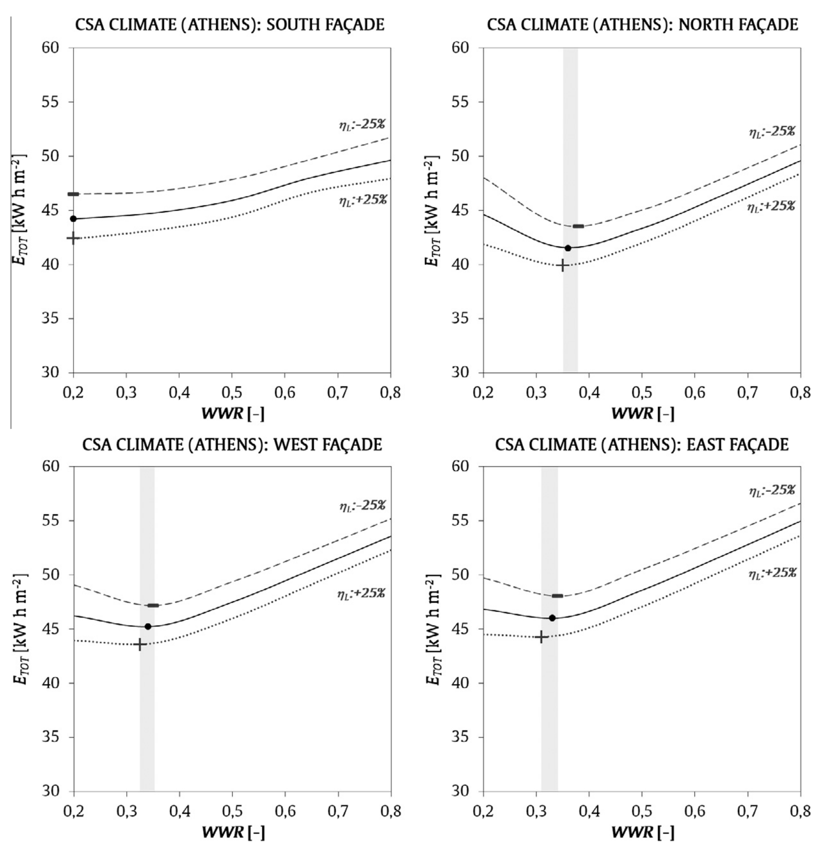

Fig. A.12. Athens – Csa: E_{TOT}(WWR) and optimal WWR for different η_L values in the four main orientations.

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